The Potential Of Fuel Cells To Reduce Energy Demands And Pollution From The UK Transport Sector

Thesis

Faculty of Technology

The Potential of Fuel Cells to Reduce Energy Demands and Pollution from the UK Transport Sector

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by

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ABSTRACT

Atmospheric carbon dioxide and pollution due to the burning of fossil fuels is increasing. Many scientists attribute global warming to the rising levels of carbon dioxide and other pollutants, some of which also pose risks to health. These can be reduced by the more efficient use of conventional fuels and the development of non-polluting energy resources. Fuel cells offer a highly efficient and low polluting method of generating electricity, and are under development for both the power generation and transport sectors. There is a need to assess (a) emissions from fuel cells using various fuels and (b) ways of introducing such technology to transportation in the near future.

Fuel consumption, energy and emissions from the production and use of fuels (hydrogen, methane, propane, petrol, diesel, alcohols and rape methyl ester) are calculated per kilowatt hour of fuel cell output over a range of efficiency. These are compared with those for internal combustion engines with advanced exhaust control and for the recharging of battery driven vehicles. The results, which are applicable to both transport and power generation, enable the best low pollution fuels to be selected and are used to calculate through life emissions for public transport buses.

Fuel cells are an ideal solution to reduce pollution from transport, but their commercial development in this field is further away than that for stationary applications. Thus, a transition stage is recommended where fuel cell electrical power stations, based on existing demonstrators, are used to recharge fleets of battery driven vehicles during the development of mobile fuel cell systems. These fleets include public transport and commercial vehicles. Also, fuel cell power stations could provide energy for electric trains. A combined system is proposed where electric trains recharge battery driven commercial vehicles during long journeys. The above proposals would enhance fuel cell development, introducing them alongside current transport systems, possibly using the same fuel.

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LIST OF SYMBOLS AND ABBREVIATIONS

AFC	alkaline fuel cell
Cp	molar heat capacity at constant pressure
Cv	molar heat capacity at constant volume
D	change in volume during reaction
E	emf of cell
F	Faraday number
G	free enthalpy or Gibbs free energy
H	enthalpy
HGV	heavy goods vehicle
ICE	internal combustion engine
MCFC	molten carbonate fuel cell
LGV	light goods vehicle
LPG	liquid petroleum gas
M_i	number of chemicals in a reaction
n_i	number of molecules of reactants
NMVOC	non methane volatile organic compounds
OHC	overhead cables
PAFC	phosphoric acid fuel cell
PEMFC	proton exchange membrane fuel cell
p_i	*partial pressure*
PM	particulate material
Q	quantity of heat
R	gas constant
RME	rape methyl ester
S	entropy of system
S_i	molar entropy
SOFC	solid oxide fuel cell
T	temperature

U	internal energy of system
U_i	internal molar energy
V_i	molar volume
W	work done
z	number of electrons

OVERVIEW OF THESIS

The main purpose of this thesis addresses the problem of reducing pollution from the transport sector whilst recognising that road congestion, particularly in urban and city areas, needs to be relieved by reducing the number of vehicles and increasing use of public transport. Thus, the methods of reducing pollution, such as alternative fuels, battery vehicles and fuel cells are compared in terms of amounts of pollutants and then applied to public transport systems. When this research was first undertaken it was aimed at a through life environmental study for a fuel cell vehicle. However, the lack of response from fuel cell manufacturers on the amounts of materials used in fuel cell manufacture made this aim untenable. Hence, it was decided to concentrate on the environmental aspects of the use of a variety of fuels and the introduction of fuel cells to the transport sector. Emphasis is on the application of fuel cells which are shown to produce the least pollution compared with batteries and internal combustion engines followed by a discussion on how they could be introduced into the transport sector.

In principle a high efficiency (45% to 65%) fuel cell using hydrogen as the fuel and oxygen from the air producing water as a by-product appears to be a perfect solution for power generation for both consumption and to drive electric transportation vehicles. In practice however, the energy and atmospheric pollution involved in manufacturing the hydrogen fuel tends to counteract the benefits unless renewable resources are used. Other options for fuels, which require processing to produce a hydrogen-rich mixture suitable for use with fuel cells, cause similar problems from their manufacture in addition to pollution from waste gases from the hydrogen-rich mixture eg carbon dioxide. Systems almost free from atmospheric pollution could be achieved by using either renewable energy sources or fuel cells for the generation of power to manufacture hydrogen fuel.

The need for reducing pollution from transport systems is reviewed, and the overall emissions from using various fuels in fuel cell systems are compared with conventional fuels and low pollution options for engines and rechargeable battery driven vehicles. Fuels considered are hydrogen, petroleum, diesel, methane, propane, methanol, ethanol and rape methyl ester. Although all of these fuels cannot yet be used in internal combustion engines or fuel cells, they are included as potential fuels.

An overall flow chart of the thesis is shown in Figure 1.

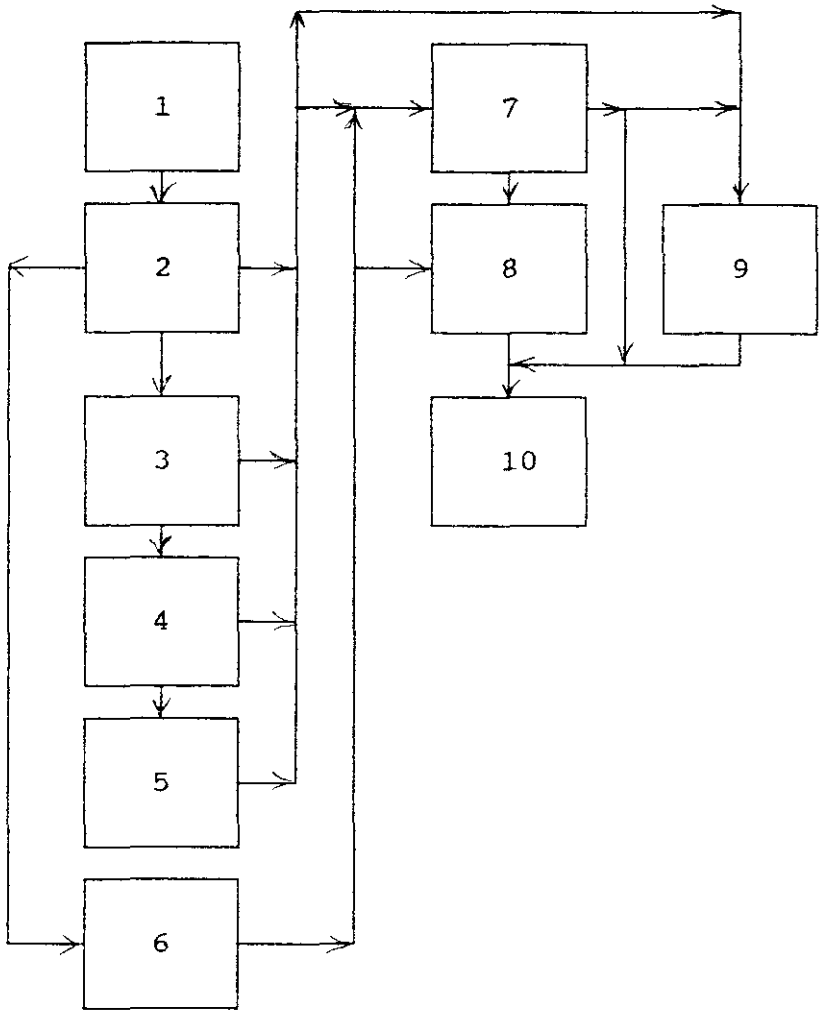
Chapter 1 considers the causes of global warming and pollution, with particular emphasis on the transport sector which contributes more to air pollution than any other single human activity. In cities and built-up areas, transport also causes more pollution than any other activity which is hazardous to public health.

Methods of reducing pollution are considered briefly in chapter 2, and past work, with particular reference to fuel cells, reviewed. The remainder of this chapter addresses the methodology and work proposed for the main analysis and comparisons in the later chapters 7, 8 and 9.

Intervening chapters deal with various topics relevant to the main theme such as fuel cells, fuels, fuel processing and electric vehicles. Each of these chapters contains a short review of past work and status of the relevant topic.

The main analysis is described fully in chapter 7 and the results are applied to environmental through life comparisons for selected public transport vehicles in chapter 8, and to the introduction of fuel cells to the transport sector in chapter 9. Calculations of emissions for fuel cells assume that, except for hydrogen which is used directly in fuel cells, the fuels are processed to produce a mixture of carbon

dioxide and hydrogen. These processes are, partial oxidation followed by a steam shift reaction to convert the carbon monoxide into further hydrogen and carbon dioxide or steam reforming followed by a CO shift reaction, They are assumed to take place externally to the vehicles, inboard vehicles or by using high temperature fuel cells with internal reforming.



1: Chapter 1. Climate, Health, Atmospheric Pollution and Transport.
2: Chapter 2. Justification and Methodology.
3: Chapter 3. Fuel Cells.
4: Chapter 4. Fuels.
5: Chapter 5. Fuel Processing.
6: Chapter 6. Electric Vehicles.
7: Chapter 7. Energy Consumption and Emissions.
8: Chapter 8. Through Life Energy and Emissions.
9: Chapter 9. Introduction of Fuel Cells in the Transport Sector.
10: Chapter 10. Conclusions.

FIGURE 1. Flow Chart

Detailed Tables of the numerical results are given in Appendix A and a summary of those for typical systems are shown in Table 1. The introduction of a new technology to the transport sector needs to be competitive with existing internal combustion engines. Potential alternatives are currently more expensive and, until firmer legislation to reduce pollution is introduced, their application is likely to remain limited to particular circumstances.

The introduction of fuel cells into the transport sector is considered in chapter 9, and includes the possibility of using a dedicated fuel cell electric power generation station to recharge battery driven public transport fleets such as buses. This is a concept which recurs throughout the thesis and is seen as a possibility to introduce fuel cells relatively quickly. Fuel cell electrical power generators using reformed natural gas have been demonstrated and could be provided to supply individual bus operators.

Also, consideration is given to applying fuel cells to other transport areas such as rail. Comparisons are made of pollutants from fuel cell power stations and conventional power stations in both of the above cases. Finally, a concept is envisaged which combines electric trains and battery driven commercial delivery vehicles, where the latter are recharged on relatively long rail journeys. This is seen as one way of relieving the congestion of heavy lorries in the UK, particularly those on long hauls from the continent.

The ideal fuel for a cleaner environment is hydrogen produced by electrolysis using renewable energy resources, but the establishment of such an economy is likely to be slow.

TABLE 1. SUMMARY OF TOTAL EMISSIONS FOR 70% EFFICIENT BATTERY (RECHARGING), 60% EFFICIENT FUEL CELL AND 35% EFFICIENT INTERNAL COMBUSTION ENGINE

FUEL	kgCO2/kWh	gCO/kWh	gCH4/kWh	gNMVOC/kWh	gNOx/kWh	gN2O/kWh	gSO2/kWh	gPM/kWh
Battery Charge (24 Hrs)	0.925	0.259	2.738	0.560	2.531	0.058	7.749	0.186
Battery Charge (Night)	0.810	0.257	2.571	1.618	2.206	0.037	6.166	0.134
FC RME (Partial Oxidation)	0.693	0.654		0.560	1.348		0.816	0.200
FC Petrol (Partial Oxidation)	0.588	0.038	0.120	1.654	0.309		0.529	0.001
FC Diesel (Partial Oxidation)	0.582	0.032	0.111	0.693	0.242		0.345	0.001
FC Biomethanol (Steam Reformed)	0.667	0.319	0.005	1.393	0.768		0.157	0.061
FC RME (Steam Reformed)	0.527	0.815		0.425	1.277		0.647	0.177
FC Bioethanol (Steam Reformed)	0.547	1.264	0.004	0.709	1.581		1.130	0.218
FC Propane (Partial Oxidation)	0.528	0.046	0.135	0.506	0.309		0.323	0.004
FC Biomethanol (Internally Reformed)	0.527	0.157		1.21	0.551		0.143	0.043
FC RME (Internally Reformed)	0.479	0.452		0.387	0.931		0.588	0.138
FC Bioethanol (Internally Reformed)	0.497	0.737		0.709	1.184		1.028	0.189
FC Methanol (Steam Reformed)	0.446	0.188	1.803	0.061	0.235			0.014
FC Petrol (Steam Reformed)	0.441	0.533	0.093	1.281	0.323	0.008	0.397	0.009
FC Diesel (Steam Reformed)	0.432	0.276	0.084	0.560	0.366	0.001	0.255	0.032
FC Petrol (Internally Reformed)	0.426	0.026	0.072	1.103	0.211		0.361	0.001
FC Diesel (Internally Reformed)	0.409	0.021	0.075	0.466	0.163		0.232	0.001
FC Propane (Steam Reformed)	0.408	0.083	0.110	0.422	0.365		0.249	0.010
FC Methanol (Internally Reformed)	0.406	0.024	1.639		0.066			
FC Methane (Partial Oxidation)	0.399	0.014	1.616	0.271	0.105		0.189	
FC Propane (Internally Reformed)	0.371	0.032	0.094	0.354	0.218		0.226	0.003
FC Methane (Steam Reformed)	0.330	0.061	1.458	0.236	0.219		0.156	0.004
FC Methane (Internally Reformed)	0.308	0.011	1.212	0.203	0.079		0.141	
FC Hydrogen (Prod. by Electrolysis)	0.097	0.027	0.287	0.005	0.266	0.006	0.813	0.020
ICE RME	1.237	6.198		2.187	8.884		1.514	0.993
ICE Biomethanol	1.026	3.427	0.103	2.743	4.221		0.278	0.348
ICE Bioethanol	1.005	10.59	0.077	2.079	8.031		2.077	0.579
ICE Diesel	0.8905	5.654	0.214	2.089	4.508	0.020	0.516	0.689
ICE Petrol	0.820	10.53	0.224	2.280	3.070	0.183	0.750	0.166
ICE Methanol	0.792	3.195	3.264		3.277			
ICE Propane	0.767	1.041	0.330	1.414	2.991		0.469	
ICE Methane	0.620	1.050	5.575	1.319	2.897		0.322	
ICE Hydrogen (Prod. by Electrolysis)	0.166	0.047	0.493	0.008	0.455	0.010	1.394	0.033

ACKNOWLEDGEMENTS

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1. CLIMATE, HEALTH, ATMOSPHERIC POLLUTION AND TRANSPORT

It cannot be denied that we are as yet very ignorant as to the full extent of the various climatal and geographical changes which have affected the earth during modern periods.
(Charles Darwin, 1859, *The Origin of Species*).

1.1 CLIMATE

The climate of the earth involves interaction between the atmosphere, oceans, ice-caps, living organisms and the solid surface. In equilibrium, radiation absorbed from the sun is balanced by that emitted by the earth. Gases in the atmosphere can retain some of the emitted radiation resulting in a net heating of the earth, known loosely as the greenhouse effect. A major climatic change due to atmospheric pollution is climatic warming due to an enhanced greenhouse effect caused by increased retention of infra-red radiation in the atmosphere, generally known as global warming. This enhancement is due to an increase in the so-called greenhouse gases, or those which cause the infra-red radiation to be retained, hence warming the lower atmosphere and the surface of the earth.

Variations in climate play an important part in the Earth's ecosystem; the proportional numbers of a country's species will almost immediately undergo a change following a climatic change, with some species becoming extinct (Darwin, 1859), and others exploiting the situation. Darwin uses this argument as a way to best understand the probable course of natural selection by going on to explain that due to the complex way in which the inhabitants of a country are bound together, any change in the numerical proportions of species, independent of the change of climate itself, would seriously affect the others.

There are many publications describing the greenhouse effect and the resultant features

of global warming, and this chapter draws on some of these, (Firor, 1990), (Leggett, 1990) and (Hughes, 1992), for background information.

1.2 GREENHOUSE GASES

Greenhouse gases are present naturally in the earth's atmosphere, the most important of these being water vapour, carbon dioxide and methane. In recent history since the advent of the Industrial Revolution, increases in the greenhouse gases have been changing the equilibrium of the climate resulting in global warming. The most common greenhouse gases increased by man's activities are:

(a) carbon dioxide, produced by fossil fuel burning and deforestation,

(b) (chlorofluorocarbons, (CFC's) and related gases, used in refrigerants and as foam blowing agents,

(c) methane, produced from rice paddies, fermentation and gas leakage,

(d) nitrous oxide, produced by biomass burning, fertiliser and combustion of fossil fuel.

1.2.1 CARBON DIOXIDE

The first gas to be considered as a potential cause of global warming was the additional carbon dioxide accumulated in the atmosphere due to the burning of fossil fuels (Arrhenius, trans. Borns, 1908). Arrhenius, although crediting Fourier for the idea that atmospheres could trap heat, recognised that the amount of coal used by the end of the 19th Century was large enough to have an effect on the concentration of atmospheric carbon dioxide. Also, he estimated the increased heating from a doubling of atmospheric carbon dioxide, and his results are well within the range from later

calculations of 2.5 to 4.5^{o}C (Doos et al, 1986).

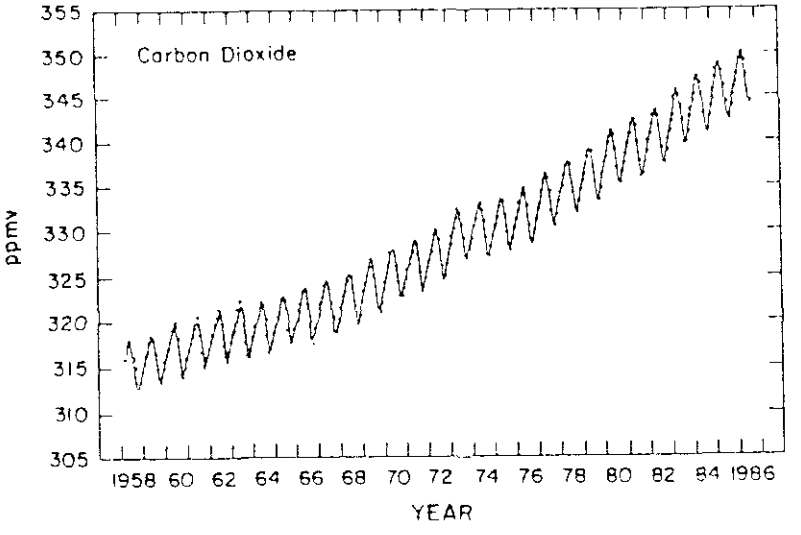
However, it was not for another fifty years after Arrhenius postulated warming of the atmosphere that evidence for increased carbon dioxide in the atmosphere was discovered, from work on radiocarbon dating. Radiocarbon dating relies on the assumption that there has always been the same fraction of C^{14} in the atmosphere. When live organic materials absorb C^{14} their fraction of C^{14} to C^{12} is the same as in air but, when the materials die the absorption stops, the C^{14} begins to decay and their ratio of C^{14} to C^{12} decreases with time. Apparent deficiencies in the expected amounts of C^{14} in modern wood (Suess, 1954) were later accounted for by an increase in ordinary carbon in the atmosphere due to the burning of fossil fuels (Revelle and Suess, 1957). They wrote: *human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years. This experiment, if adequately documented, may yield a far-reaching insight into the processes determining weather and climate.*

This statement is scientific in nature, pointing out that use could be made of an accidental experiment. Later comments by others take on a more sinister note, implying that we are experimenting with the earth without knowing the eventual results. Prime Minister Mrs Thatcher in 1988 referred to *a massive experiment with the system of this planet itself* (Milne, 1989).

Since the original work comparing dating by recent tree rings with that by using C^{14} (Suess, 1954), the rate of burning fossil fuels has increased considerably but the amount of C^{14} also has increased significantly due to the atmospheric testing of nuclear weapons in the 1950s and 1960s, temporarily masking the effect and making further measurements difficult.

Since 1958, carbon dioxide concentrations in the atmosphere have been measured at the

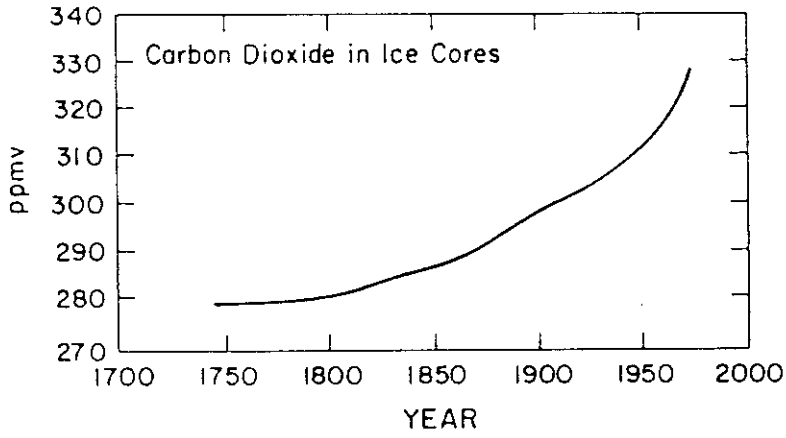
Mauna Loa observatory in Hawaii where the air samples are drawn from high above the site and away from natural and industrial contamination. These measurements have shown an increase since 1958 at a rate which accelerates, and are sufficiently sensitive to show the annual oscillation due to plants absorbing carbon dioxide from the air during the growing season and returning it during the decaying season in the autumn (Carbon Dioxide Information Centre, Oak Ridge National Laboratory, USA, 1958-1990). The overall increase from 1958 to 1990 is shown to be from about 315 ppm to 359 ppm by volume, see Figure 1.1.



The concentration of carbon dioxide in the air as measured at the Mauna Loa Observatory from 1958 to 1986. Units of concentration are parts per million by volume.

Figure 1.1 (Oak Ridge National Laboratory, 1990)

Measurements of carbon dioxide in the air for the years back to 1750 have been made from air samples trapped in cores taken from the polar ice (Friedli et al, 1986). These measurements show, see Figure 1.2, that a rapid increase in atmospheric carbon dioxide started about two hundred years ago and has accelerated in the 20th Century. This increase corresponds with increased burning of fossil fuels since the start of the industrial revolution.



The concentration of carbon dioxide found in air trapped at different depths in polar ice. The concentration is in parts per million by volume.

Figure 1.2 (Friedli et al, 1986)

Much work on measured and predicted global temperature measurements has been carried out and is considered later in section 1.3, below.

1.2.2 CHLOROFLUOROCARBONS

CFCs, by releasing chlorine under the action of ultraviolet radiation from the sun, especially in the stratosphere where UV is more intense, reduce the amount of ozone in the earth's atmosphere. In the high atmosphere or stratosphere ozone has an important role in relation to life on earth. Under the action of strong sunlight oxygen (O_2)breaks down into atoms (O), some of which react to produce ozone (O_3) which in turn absorbs UV radiation, particularly UV-B. UV-B is capable of changing biological material such as causing sunburn and affecting crop yields.

Initially, concerns about depletion of the ozone layer in the stratosphere centred on the exhaust from high altitude aircraft and space rockets, but soon changed to the realisation that CFCs were produced in far greater quantities (Dotto and Sciff, 1978). In particular, two CFCs, CFC-11 and CFC-12 have proved so valuable in many

industrial applications that more than 20 million Tonnes have been manufactured, most of which has or will, escape to the atmosphere.

The first measurements of atmospheric CFC concentrations at various locations since 1978 have shown rates of increase of about 5 ppt/yr to 14 ppt/yr by volume for CFC-11 and CFC-12, respectively (World Meteorological Organisation, 1985). Later, in 1987, it was recognised that in spring each year, starting in the late 1970s, the total amount of stratospheric ozone over Antarctica had been decreasing, and by a larger amount each year. In the Southern Hemisphere from 1979/80 to 1987/88, annual mean percentage losses of more than 9% extended in parts to latitude 55^{O}S. Losses up to 7.5% extended in parts to latitude 50^{O}, those up to 6% extended in parts to latitude 34^{O}S and those up to 4.5% extended in parts to latitude 30^{O}S. In the Northern Hemisphere, the areas of loss are more sporadic but at longitude 70^{O}W the 4.5% area extends to about latitude 12^{O}S (Seager, 1990). Later measurements in the Antarctic (Hofmann, 1996) indicate that the remaining ozone at an altitude range of 12-20 km has shown a consistent downward trend in the last 10 years.

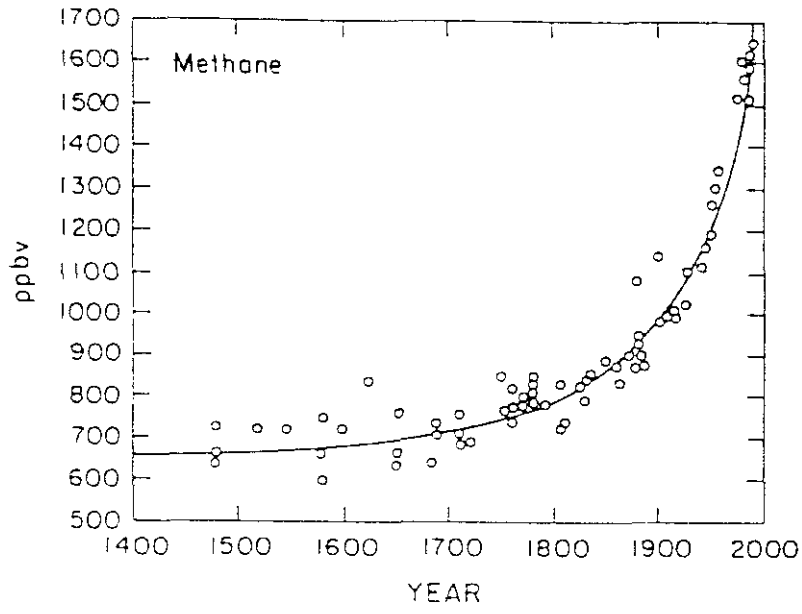
In 1989 the Montreal Protocol, a treaty to phase out the production of CFCs and halons that had a potential to deplete stratospheric ozone, was agreed by most industrial countries except China and India. Also, in 1996 a ban on the production of various CFCs and halogens was required (World Meteorological Organisation, 1995). Continuous monitoring of the total ozone destroying potential of the atmosphere (in terms of total equivalent chlorine) now indicates this potential peaked in the troposphere in 1994 and, if the Montreal Protocol is effective, will peak in the stratosphere between 1997 and 1999 (Montzka, 1996), and pre-ozone-hole levels should be reached by 2050 (Hofmann, 1996).

Recent measurements (Fahey, 1997) have been reported (Pearce, 1997) which sampled the exhaust from a high altitude flying Concorde aircraft have again raised the possibility of such exhausts depleting the ozone layer, as mentioned above. The exhaust in the aircraft's slipstream, sampled ten minutes after it had passed, is found to

contain sulphuric acid in the form of a very fine aerosol. It is considered that the Concorde aircraft produces sulphur trioxide rather than sulphur dioxide, resulting in much more rapid conversion to sulphuric acid. This, combined with any scarcity of atmospheric particles on which the acid can condense, creates a fog of acid particles. The number of these particles in the stratosphere can affect the ozone loss by increasing the number of sites on which chlorine from pollutants can destroy atmospheric ozone. An increase in the number of supersonic high altitude aircraft could have a direct effect on stratospheric ozone, and the exhaust from high flying subsonic aircraft needs to monitored (Fahey, 1997). At lower altitudes, subsonic aircraft could encourage the formation of cirrus clouds, contributing to global warming.

1.2.3 METHANE

Measurements of the atmospheric concentration of methane gas show that it is increasing at twice the rate of that for carbon dioxide. Direct measurements from air samples have been made since 1950 and from air samples trapped in ice cores dating from 1480, and were first published in the 1980s (Rasmussen and Khalil, 1984), (Stauffer et al, 1985) and (Blake and Rowland, 1986). These measurements, see Figure 1.3, show an increase from 1480 to 1750 of about 660 ppb to 740 ppb by volume whereas, from 1750 to 1986 the increase is from about 740 ppb to 1700 ppb by volume in 1990.



The concentration of methane in the atmosphere at various times in the past, as deduced from measurements of air trapped in ice cores (1450–1950) and from direct measurements of air samples (after 1950). The concentration is plotted in parts per billion by volume

Figure 1.3
(Firor (1990)

1.3 CLIMATE HEATING

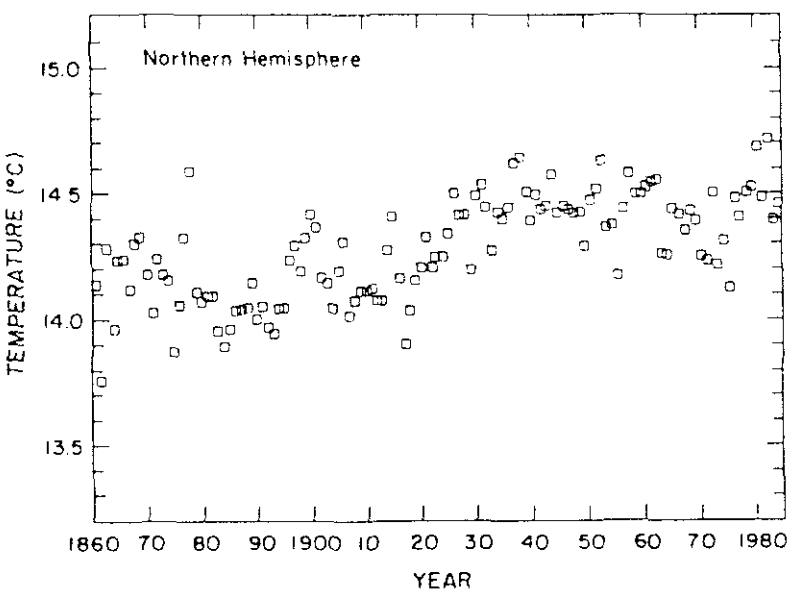
There is certainly good evidence of the growth in emissions of the above gases, but is this sufficient to affect the World's climate?

1.3.1 TEMPERATURE

Climatic records for various global sites exist for the last two centuries and detailed records exist for the last one hundred and fifty years. However, particular locations may be influenced by local human activities and to calculate an average global temperature a very large number of locations must be used. One difficulty is that most of the earth's surface is covered by oceans and there are very few records made at sea that could be used with the land-based records. This difficulty has been overcome by including measurements from ships, either of the air or of the surface seawater, in the

average global temperature from the years 1860 to 1985 (Jones, Wigley and Wright, 1986). This gives much smaller changes over each decade than for land based measurements but a clear average increase of $0.5^{o}C$ over 120 years for both the Northern and Southern Hemispheres, see Figure 1.4 and 1.5.

Estimates of average global temperatures based on climatic models and temperature measurements for later years using weather artificial satellites are discussed later in this section. Comparisons between model predictions and temperature measurements are also discussed then.



The surface temperature of the Northern Hemisphere since 1861, as deduced from measurements over land and ocean areas and of the temperature of the water at the ocean surface.

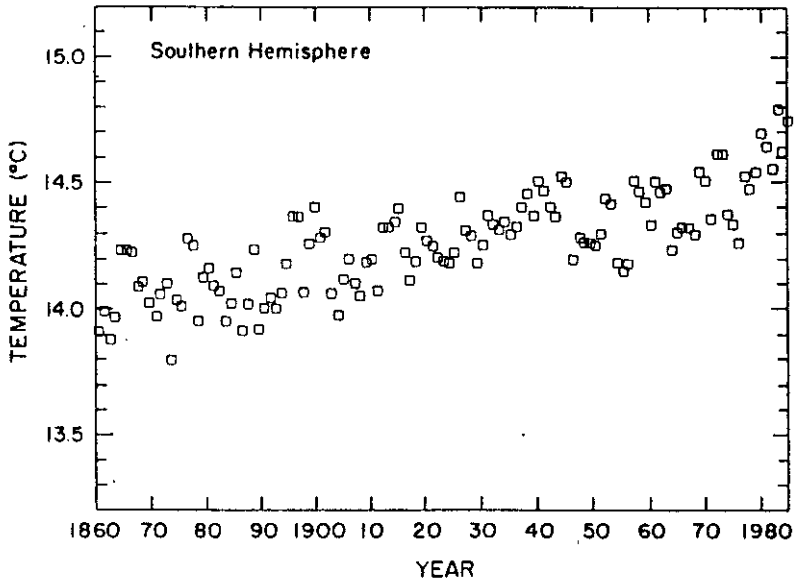
Figure 1.4 (Jones, Wigley and Wright, 1986)

The recent retreat of tropical alpine glaciers and of the polar icecaps (Thompson, 1995), plus changes in alpine freezing levels (Diaz and Graham, 1996) have tended to support an overall positive trend in global temperature.

An analysis of global surface air temperature records indicates that recent years have been some of the warmest since the late 19th century (Houghton, et al, 1996), with 1995 the warmest year. (Hansen et al, 1996).

Models for the Earth's climate have been used to predict future changes and have been compared with past records. Such simulations imply that the temperature response is markedly greater for carbon dioxide forcing than for aerosols. (Taylor and Penner, 1994). One model from the Hadley Centre at the Meteorological Office, Bracknell has successfully reproduced past fluctuations in the Earth's temperature (Matthews, 1994). It includes estimates of past sulphate production and accounts for all major trends in global warming since the year 1860. Past temperatures are shown to be approximately constant from the years 1860 to 1920, rising by $0.3^{O}C$ during the 1930s and 1940s, relatively stable until the year 1970 and then climbing continuously by 1994 to about $0.3^{O}C$ above the average for the years 1951 to 1980. These changes are seen as the results of industrialisation and changes in the world such as increased energy use in transport systems. The first temperature plateau is seen as due to the effect of sulphate particles in the atmosphere from the use of fossil fuels offsetting the carbon dioxide warming. Both of the later rises in temperature are seen as due to the accumulation of carbon dioxide ultimately overcoming the cooling effect from sulphate particles, resulting in an overall rise in temperature.

Models which are driven by increasing concentration of carbon dioxide predict the same amount of warming by day and night (Harvey, 1995). Harvey quotes that records from the years 1951 to 1990 (Hansen, Slater and Ready, 1995) show that the average daily maximum of land surface air temperature has increased by $0.28^{O}C$, and that the corresponding minimum daily temperature has increased by $0.84^{O}C$. This is explained in terms of regional increases in the aerosol optical depth, low level clouds



The surface temperature of the Southern Hemisphere since 1961, as deduced from measurements over land and ocean areas and of the temperature of the water at the ocean surface.

Figure 1.5 (Jones, Wigley and Wright, 1986)

and a large scale warming effect such as increases in greenhouse gases. This work is seen as providing a broad quantitative explanation of current observations as well as further evidence that continued increase in greenhouse gases will lead to socially and ecologically important climate changes.

A later paper (Mitchell et al, 1995), indicates that contemporary models suggest that increases in greenhouse gases in the atmosphere should have produced a larger global mean warming than has been observed in recent decades, unless the climate is less sensitive than predicted by present models. In their paper (Mitchell et al, 1995) a new coupled ocean-atmosphere model simulates past and future climate since near-global instrumental surface temperature records have begun, which agrees with the observations up to the year 1994. These observations giving a global mean temperature change of $0.5^{o}C$ from the years 1900 to 1994 are quoted from (Houghton, 1995). Also, the new model predicts future warming of $0.3^{o}C$ per decade for greenhouse gases alone, or $0.2^{o}C$ per decade with sulphate aerosol forcing included, and suggests that global warming could accelerate as greenhouse gas forcing begins to dominate over

sulphate aerosol forcing. The overall predicted figure is a mean global warming of 1.8^{o}C from the years 1900 to 2050.

A statistical analysis (Santer et al, 1996a) compares a model generated thermal structure of the atmosphere due to the increase of greenhouse gases and the reduction of ozone, with the observed thermal structure between 1963 and 1987. This comparison shows that the pattern correlation between the predicted and observed changes in zonal mean latitude height profiles of atmospheric temperature increases with time. Others (Michael and Knappenberger, 1996) and (Weber, 1996) have criticised these conclusions claiming that more complete data is required; these have been answered (Santer et al, 1996b) claiming that the primary conclusions of Santer et al (1996a) still stands. Thus, arguments for and against global warming due to human activities continues.

An analysis of the predictions of computer simulations from the period 1979 to 1989, and reported in The Times (Hargrave, 1997), indicates that predicted temperatures are considerably greater than measurements from weather artificial satellites. The predictions are between four and ten times greater than data from the measured data, giving a predicted decadal atmospheric temperature rise of between 0.13 and 0.35^{o}C compared with 0.03^{o}C from satellite data. It is claimed that the earlier models failed to consider the shielding effect of sulphur in the atmosphere and the ability of certain atmospheric areas to transmit heat into outer space.

The comparison of satellite measurements, from which the temperature of the global lower tropospheric temperature is inferred (Hurrell and Trenberth, 1997) indicate that this temperature has decreased by -0.05^{o}C per decade compared with the annual global surface warming of 0.13^{o}C per decade (Christy et al, 1995). This difference has been used as an argument for evidence against global warming (Economist, 1996 and Singer, 1996). However, the satellites record radiance using microwave sounder units (Spencer and Christy, 1992), a large fraction of which is due to radiation from the Earth's surface rather than the atmosphere (Shah and Rind, 1995). This radiation from

the Earth's surface gives rise to noise levels which can lead to errors when merging results from different satellites (Hurrell and Trenberth, 1997). Comparisons have been made for the tropics, where atmospheric temperatures are tied closely to sea surface temperatures, between:

(a) temperature measurements derived from different satellite microwave records,

(b) equivalent temperatures derived from microwave values derived from an atmospheric circulation model using observed sea surface temperatures,

(c) observed sea surface temperatures.

These comparisons suggest two spurious downward temperature jumps occur with time in the microwave records which coincide with changes in the satellites used, and that the correct trend is likely to be positive (Hurrell and Trenberth, 1997). Also, it is argued that since the surface records and satellite records are for different physical quantities (temperature and radiance), the decadal trends should not be expected to be the same (Hurrell and Trenberth, 1996). This is particularly relevant when it is considered that other annual variations associated with volcanic eruptions and ocean currents, can affect atmospheric and sea vertical temperature structures (Christy and McNider, 1994, Jones, 1994 and Hurrell and Trenberth, 1997).

Projections of future climate change depend upon the results of predictions using computer models of the Earth's climatic system and much discussion continues (Trenberth, 1997) and as indicated above. Overall, the results summarised in this section indicate that global warming is certainly happening, but at a rate less than some models suggest. The uncertainties in climatic modelling and in the prediction and measurement of temperature changes could indicate that an increased understanding of all the processes involved is needed, and that they all need to be accounted for by the models.

1.3.2 SEA LEVELS

Climatic heating might bring a rise in sea level due to glacial melting and the thermal expansion of sea-water, which could have serious results. In the absence of efforts to decrease greenhouse gas emissions, estimates (IPCC, 1990) indicate that by the year 2030 sea levels will rise by between 20 and 30 cm; by the end of the next century this rise could be as high as 30 to 100 cm. Estimates on the loss of estuaries, shorelines and wetlands would be serious; the UK could lose much of its sand beaches, salt marshes and mud flats (Boorman et al, 1989), and the USA could lose up to one half of wetlands in the next century (Titus, 1986). However, uncertainties in climatic modelling and predictions of future temperature changes, as indicated above, could change this view.

1.3.3 OTHER EFFECTS

Other major effects of climatic heating could be increased desertification and more extremes in the weather pattern such as those due to temperate climates becoming warmer and increased uptake of water vapour from the oceans. These changes could have a serious effect on food production, particularly for the developing countries, and on health of other areas due to the possible spread of tropical diseases.

1.4 SUMMARY ON POLLUTION AND CLIMATE

The previous sections on climate started with a brief reference to Darwin and his opinion as to the migration and extinction of species due to climatic changes influencing the course of natural selection or the survival of the fittest. The foregoing also has sought to summarise the effect of mankind's activities over the last 200 years and to indicate that, as a result, changes in climate might occur in the future. Although mankind would probably adjust to these changes, they could result in social, economic

and political tensions. The real questions are whether or not this adjustment is the best course and whether or not increased efforts should be made to reduce the activities causing the pollution.

To summarise, the mechanism of global warming first postulated by Arrhenius (1908) has withstood crucial tests and criticisms. To date, even though some critics are of the opinion that the analysis of further data is required, and that different methods give different results in atmospheric temperature changes, the overriding scientific opinion is that global warming will continue unless measures are taken to moderate the contributing factors produced by mankind's activities. The major effects of global warming, if allowed to continue will be harmful to mankind and to natural systems. It will be seen later that emissions from the transportation sector are thought by some to be a major contributor to global warming and, if allowed to continue unchecked, could have a harmful effect on both health and climate.

As indicated above, uncertainties in climatic modelling and in both the prediction and measurement of changes in the mean global atmospheric temperatures could change this view.

1.5 HEALTH

Global warming could also affect the health of the human population as well as having adverse effects on food production, water resources and coastal flooding. Additionally, pollution products from industry and transport vehicles present health problems other than an increase in temperature.

Carbon monoxide produced from vehicle exhausts is linked with lethargy and dizziness and is lethal in high concentrations. New health guidelines will limit concentrations to 10 ppm averaged over 8 hours.

Particulates, which consist of small sooty particles and can be coated in hazardous

chemicals, are produced from diesel vehicles, boilers, tyre wear and fires. They cause breathing difficulties and have been linked with asthma and heart attacks. New health guidelines will limit concentrations to 50 microgrammes per cubic metre averaged over 24 hours.

Oxides of nitrogen, produced mainly from vehicle exhausts and formed when fuels are burnt in air at temperatures above about $1000^{o}C$, have been linked with breathing difficulties and asthma. Current health guidelines limit concentrations to 210 ppb averaged over one hour and new guidelines will reduce this to 105 ppb over on hour and 20 ppb averaged over one year.

Benzene, C_6H_6, linked with cancer and leukemia, is present in petroleum fuel and released from leakages at oil refineries and petrol stations and from unburnt fuel in vehicle exhausts. New health guidelines will limit concentrations to 5 ppb averaged over one year.

Sulphur dioxide, produced from coal and oil burning power stations and in vehicle exhausts, causes breathing difficulties. Current health guidelines limit concentrations to 175 ppb averaged over 10 minutes and new guidelines will reduce this to 100 ppb averaged over 15 minutes.

Lead, present in fuels, is a poison which affects the brain and is now being extracted from many petroleum fuels. Although leaded petrol is still widely available, the gradual changeover to unleaded petrol and the reduction in the numbers of older cars will reduce this risk. Current health guidelines limit concentrations to 1 microgramme per cubic metre averaged over one year and new guidelines will reduce this to 0.5 microgramme.

Ozone, formed by the action of bright sunlight on vehicle exhaust and from dry cleaners, paint and chemical production, is linked with breathing difficulties, asthma and lung cancer. Health guidelines limit concentrations to 50 ppb averaged over 8

hours.

Butadiene, C_4H_6, a solvent present at low levels in petroleum and diesel, is linked to leukemia and lymphonas. New health guidelines will limit concentrations to 1 ppb averaged over one year.

The remainder of this thesis deals with the effects of pollution from transport vehicles and the means by which these can be reduced. The effects of road vehicle exhaust emissions in cities and towns has been highlighted in recent reports as being a major cause for concern.

1.6 POLLUTION FROM TRANSPORT VEHICLES

In cities transport vehicles generate more pollution than any other single human activity and greenhouse gases emitted by or attributable to this source are CFCs, carbon dioxide, nitrous oxide, methane, hydrocarbons, nitrogen oxides (NO_x) and carbon monoxide. Pollutants which are harmful to health and emitted by, or caused by the use of, vehicles are carbon monoxide, particulates, nitrogen oxides, hydrocarbons, sulphur dioxide, lead and ozone.

CFCs are one of the most potent of greenhouse gases, contributing about 24% to global warming (IPCC, 1990). Between 30 and 40% of the United States' and European production of CFC's is devoted to air-conditioning and refrigeration, about 13% of which is used in mobile air-conditioning (Walsh, 1990).

Carbon dioxide contributes about 55% to global warming and transport consumes almost one third of the total world production of energy, highly dependent on regional usage, resulting in about 25% of the total output (IPCC, 1990). In particular, the USA and Europe account for as much carbon dioxide emission from transport as the rest of the world combined. Of the remaining pollutants emitted globally, transportation is responsible for about 66% of the carbon monoxide, about 47% of the nitrogen oxides

and about 39% of the hydrocarbons (Walsh, 1990).

The carbon dioxide and CFCs emissions from motor vehicles contribute to global warming by direct action in the atmosphere. Carbon monoxide emission does not trap infra-red radiation directly but tends to react with other compounds, such as hydroxyl radicals (OH), causing a reduction of these in the atmosphere. Since a reaction between hydroxyl radicals and greenhouse gases such as methane normally tends to remove these gases from the atmosphere, this reduction results in more methane rising to the upper atmosphere (Walsh, 1990). Further, the emitted carbon monoxide is eventually converted into carbon dioxide, and thus it effects the atmosphere in two ways: a methane effect and a carbon dioxide effect. On a per unit mass basis methane has a greater impact on global warming than carbon dioxide, and is estimated to 2.2 times higher (Lashof and Ahuja, 1990). Thus, the control of carbon monoxide emissions from vehicles is a better strategy for reducing global warming than allowing the carbon to be emitted as carbon dioxide directly.

As detailed later, it should be noted at this point that the use of fuel cells with pure hydrogen as a fuel for transportation would reduce the above emissions from such vehicles to virtually zero. If a hydrocarbon or an alcohol such as methanol were used as the fuel this would, because of increased efficiency, result in reduced emission of carbon dioxide and sigificant reductions for the other pollutants.

1.7 WORLD TRENDS FOR MOTOR VEHICLES

Up to the year 1945 the increase in motor vehicles was relatively small, but since 1950 the average annual growth rate has been 5.9% for cars and 5.6% for larger vehicles. The overall trends since the year 1930 are shown in Figure 1.6 (Walsh, 1990).-

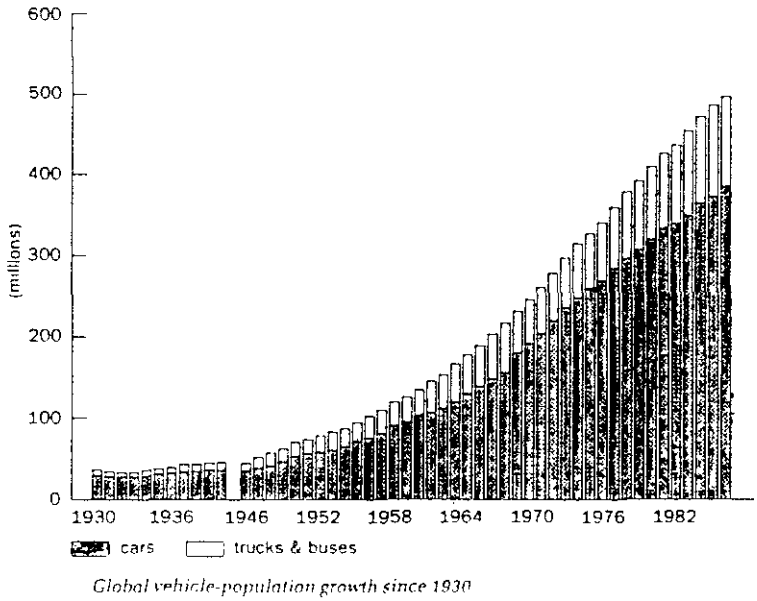


Figure 1.6 (Walsh, 1990)

Future emissions of greenhouse gases from motor vehicles have been estimated (Walsh, 1990) for various global regions: European Community (EC), European Free Trade Association (EFTA), North America (NA), Japan/Australia (JA), Rapidly Industrialising Countries (RIC) and the rest of the world (ROW). In each case, emission standards judged likely to apply at a given time were those which have already been adopted and either are in effect or are estimated to come into effect in the future years.

Future global trends in motor vehicle emissions of carbon monoxide, hydrocarbons and nitrogen oxides are shown in Figure 1.7 assuming that current patterns are continued. A steady reduction in emissions is shown for the 1990s, due to the recently adopted emission requirements in Europe and further proposed reductions in the USA. However, by the year 2000 the emission rates will have bottomed and will start to increase unless further controls are introduced.

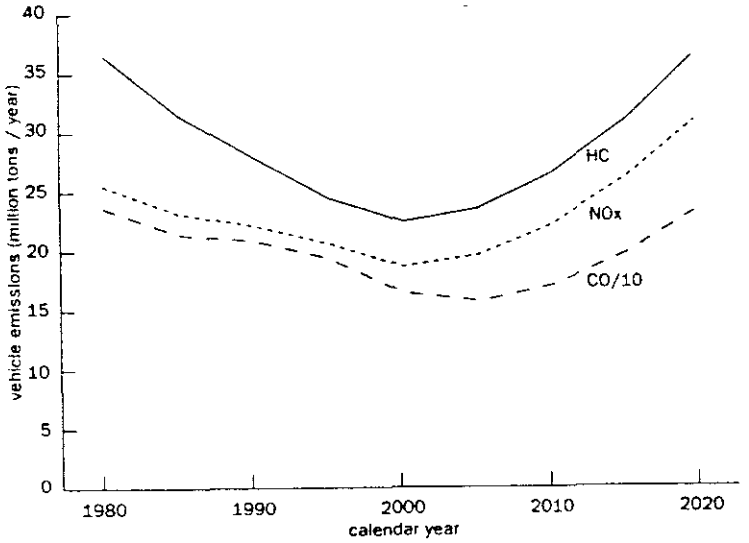
The greatest growth is then likely to be in the rapidly industrialising areas of the world (RIC) and the rest of the world (ROW) where controls virtually do not exist, while the

highly industrialised areas (EC, EFTA, NA and JA) still remain as the dominant source of motor vehicle emissions. These regional effects are shown in Figures 1.8 to 1.10 for hydrocarbons, carbon monoxide and nitrogen oxides respectively.

However, Walsh, (1990) considers a second scenario where all vehicles around the world are assumed to adopt state-of-the-art emission controls. This scenario indicates that it has the potential to offset the emissions from growth in the global vehicle population, as shown in Figures 1.11 to 1.13. These show that the introduction of state-of-the-art emission controls start to reduce global emissions of carbon monoxide, hydrocarbons and nitrogen oxides while at the same time absorbing the effects of an average 3% annual growth rate in motor vehicles. However, the figures also show that continued growth in vehicle numbers increases emissions again after the year 2015. Figures 1.14 to 1.16 show that emission controls in the various regions are not sufficient to overcome the projected vehicle growth.

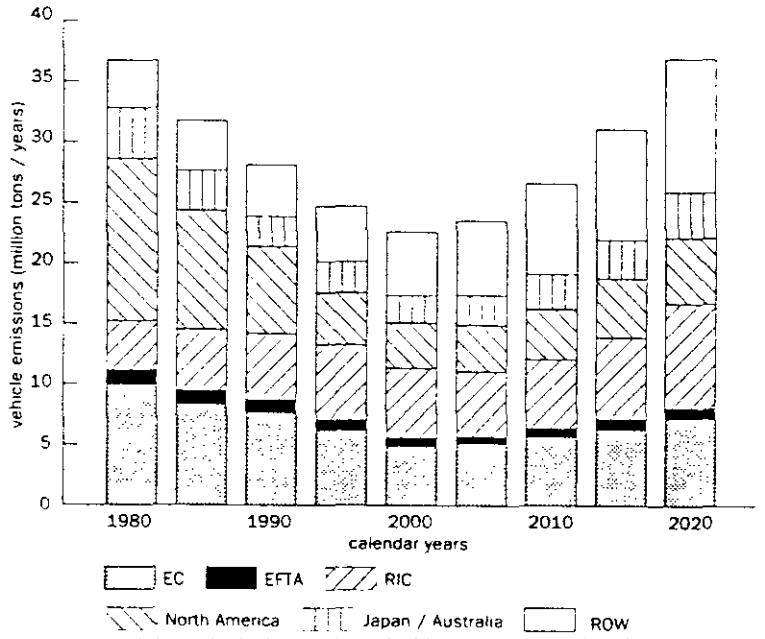
Emissions of carbon dioxide from motor vehicles, based on projected increases in vehicle numbers, increase rapidly over the next two decades as shown in Figure 1.17. The lowering of this trend could be achieved by reducing the vehicle miles per year, reducing the number of vehicles or the use of more efficient vehicles, but a combination of all three will probably be required.

Figure 1.18 shows the effect of a 2% increase in the efficiencies of new vehicles which, if combined with a reduction in the growth of vehicle numbers, could begin to reverse the increase in global carbon dioxide emission from road transport. However, simply holding down the level to today's high is insufficient to reverse the effects on global warming. This figure includes the additional effect of the annual conversion of 2% of vehicles to fuel cells from the year 2000, followed by 3% after the year 2010. Targets set by the IPCC (1991, 1995) include a cut of at least 50% in carbon dioxide in order to stabilise atmospheric concentrations and to reduce the rate of global warming.



Trends in vehicle emissions of HC, CO, and NO_x as a result of the projection of currently adopted requirements (for CO, multiply vertical scale by 10)

Figure 1.7 (Walsh, 1990)



Trends in total vehicle emissions of HC by region as a result of the projection of currently adopted requirements

Figure 1.8 (Walsh, 1990)

1.8 TRANSPORT TARGETS

Targets have been published from the Royal Commission on Environmental Pollution aimed at reducing transport congestion, increasing air quality and improving public health (Hamer, 1994). These refer to increasing rail and water-borne freight, reducing car journeys in London and other urban areas, increasing air quality and reducing carbon dioxide emissions from transport, with the following specific targets for by particular years.

By the year 2000:

(a) to increase rail freight by 50%,

(b) to increase water-borne freight by 20%,

(c) to reduce the number of car journeys in London from 50% to 45% of all journeys,

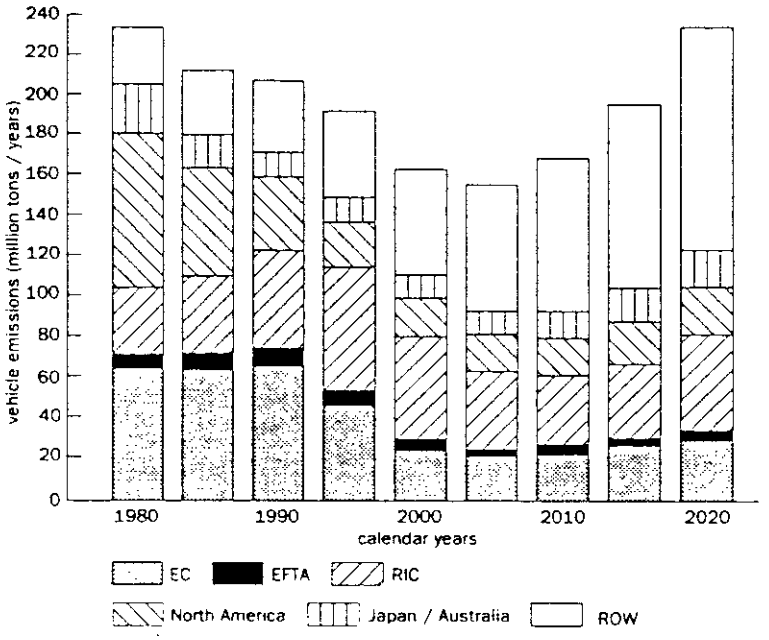
(d) to reduce car journeys in other areas from 65% to 50% of all journeys,

By the year 2005:

(a) to increase air quality to World Health Organisation guidelines,

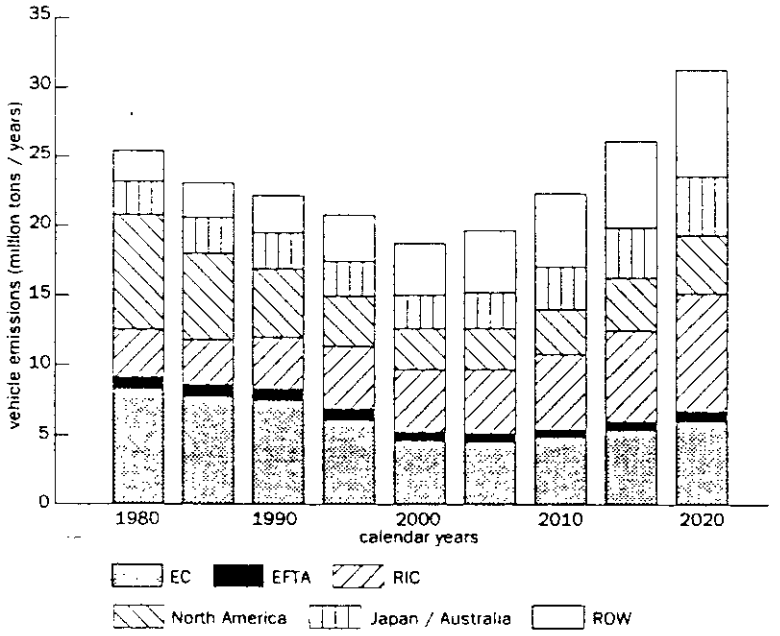
(b) to increase public transport use by 66%,

(c) to quadruple bicycle use in urban areas,



Trends in vehicle emissions of CO by region as a result of the projection of currently adopted requirements

Figure 1.9 (Walsh, 1990)



Trends in vehicle emissions of NO_x by region as a result of the projection of currently adopted requirements

Figure 1.10 (Walsh, 1990)

By the year 2020:

(a) to reduce carbon dioxide emissions from transport to 80% of 1990 level,

(b) to reduce number of car journeys in London to 35% of all journeys,

(c) to reduce number of car journeys in other urban areas to 50% of all journeys.

To date, the UK government has rejected setting specific targets except for *overall* reductions in carbon dioxide by the year 2000 to levels for the year 1990.

The United Nations Economic Commission for Europe recommends emission standards but cannot enforce them. The European Economic Community (ECE) sets standards which have generally been adopted by the European Community and non-EC countries. Some European countries, Scandinavia, Switzerland and Austria, have adopted tighter standards based on legislation in the USA. The ECE regulations which affect heavy duty vehicles are summarised in the following Table (1.1 from ETSU, 1994a).

TABLE 1.1

(ECE Regulation 49.01 Heavy Duty engine emission limits)

(g/kWh)

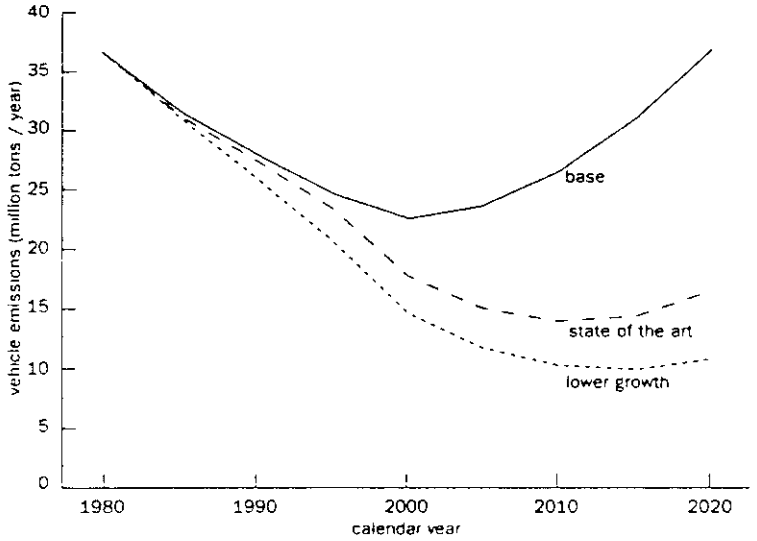
CO	HC	NOx
11.2	2.4	14.4

Two further compulsory stages are shown in TABLE 1.2.

TABLE 1.2

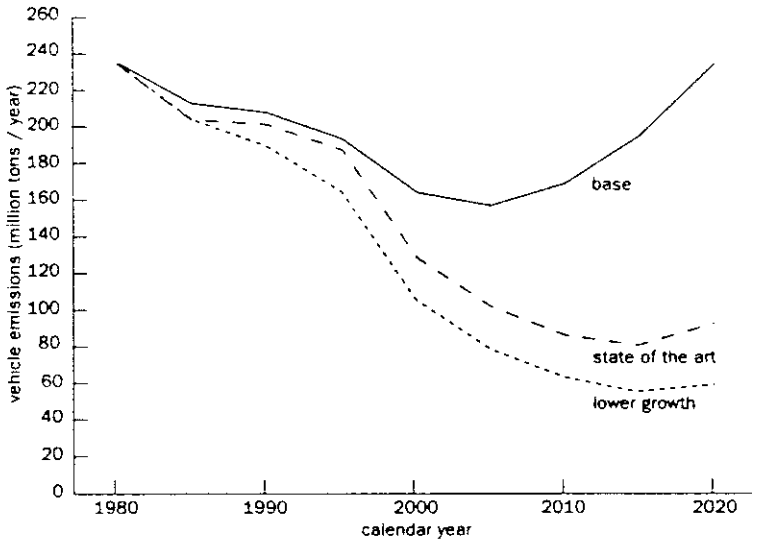
(g/kWh

Emission	Effective 1992	Effective 1996
CO	4.5	4.5
HC	1.1	1.1
NOx	8.0	7.0
PM	0.33	0.15



Trends in vehicle HC emissions if all vehicles around the world used state-of-the-art emission controls

Figure 1.11 (Walsh, 1990)



Trends in vehicle CO emissions if all vehicles around the world used state-of-the-art emission controls

Figure 1.12 (Walsh,1990)

An appraisal of future development (ETSU, 1994a) assumes that the development of low emission technologies for IC engines and future increased political pressure will result in lower emissions for various vehicle categories as shown in Tables 1.3 and 1.4.

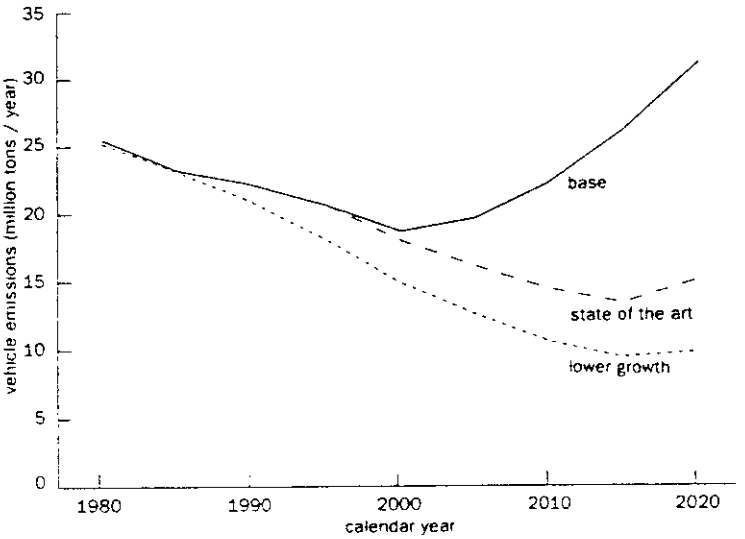
TABLE 1.3

(Emissions for Bus Technologies)

(g/MJ Fuel)

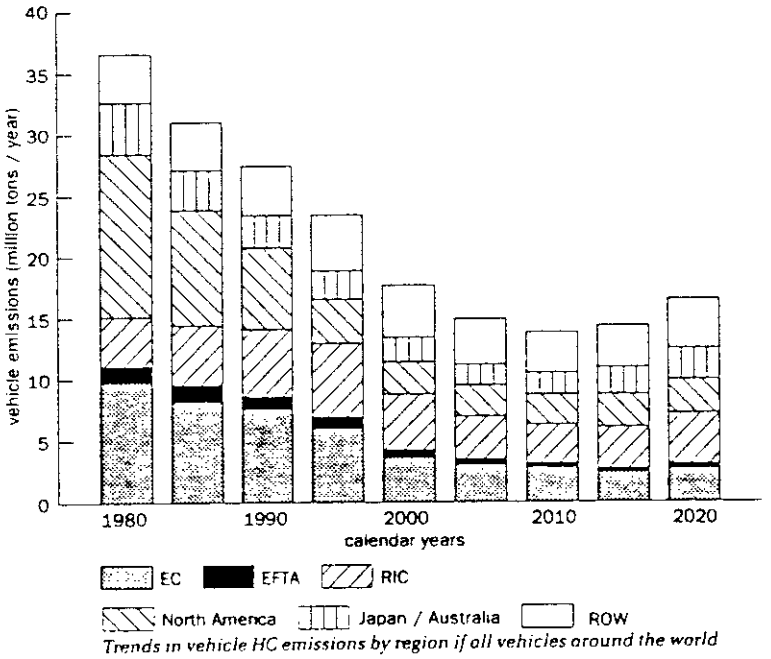
Bus Technology	Carbon Dioxide	Nitrogen Oxides		Sulphur O_2	
	1990-2030	1995 -2005	After 2005	1995 -2000	After 2000
Min. Change	69.3	0.206	0.128	0.07	0.02
Advanced Techy.	69.3		0.163		0.02
CNG/Diesel	50.6	0.158	0.092	0.016	0.005
Bioethanol		0.111	0.069	0	0
Bioethanol		0.111	0.069	0	0

Biofuels are discussed later in Chapter 4, and the above Table assumes zero net CO_2 emissions over the total period covering crop growth and fuel usage.



Trends in vehicle NO_x emissions if all vehicles around the world used state-of-the-art emission controls

Figure 1.13 (Walsh, 1990)



Trends in vehicle HC emissions by region if all vehicles around the world used state-of-the-art emission controls

Figure 1.14 (Walsh, 1990)

TABLE 1.4

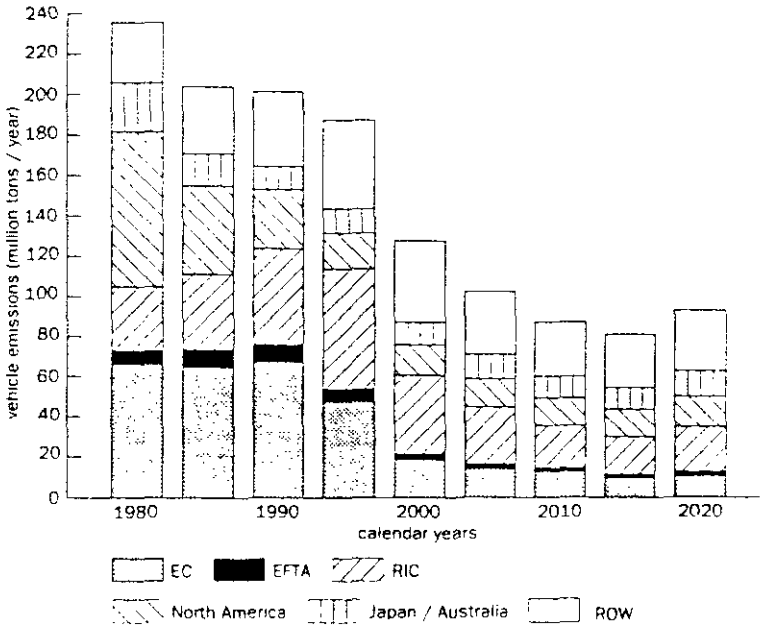
(Emissions for HGV Technologies)

(g/MJ Fuel)

HGV Technology	Carbon Dioxide	Nitrogen Oxides		Sulphur O_2	
	1990-2030	1995	After 2005	1995	After 2000
		(Small HGVs)			
Min. Change	69.3	0.388	0.243	0.07	0.02
Advanced Techy,	69.3		0.25		0.02
CNG/Diesel	50.6	0.292	0.194	0.006	0.002
		(Large HGVs)			
Min. Change	69.3	0.45	0.278	0.07	0.02
Advanced Techy.	69.3		0.278		0.02
CNG/Diesel	50.6	0.333	0.222	0.016	0.005

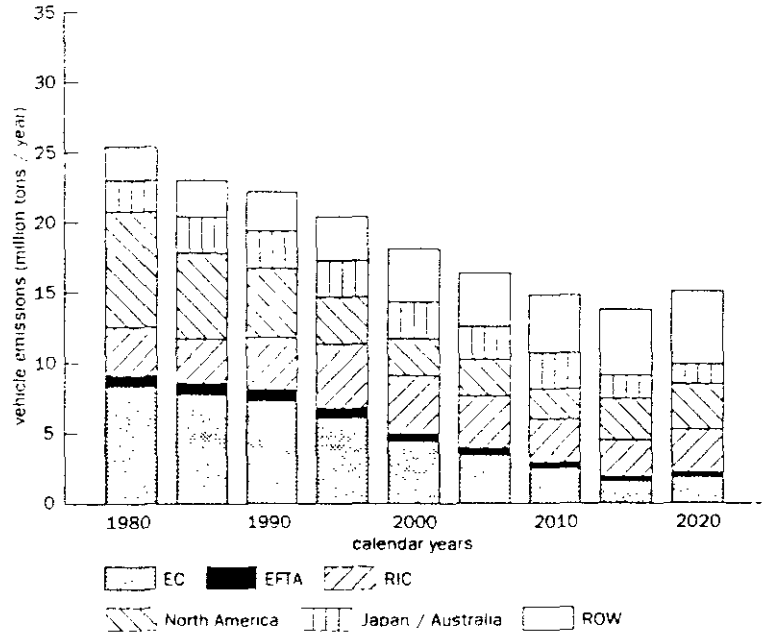
1.9 SUMMARY ON POLLUTION FROM TRANSPORT

As indicated above, there are a number of pollutants from the transport sector which are injurious to health. In addition to the congestion of traffic, as the number of vehicles increases with time, particularly in city and urban areas, these pollutants could become a serious problem. The methods considered here (Walsh, 1990) to reduce emissions from road transport do not start to have a significant effect until after the year 2000, and then emissions start to increase again after the year 2005 or 2020, depending upon the method considered. Thus, traffic growth starts to reduce the potential of these methods and in time, results in increasing pollution.



Trends in vehicle CO emissions if all vehicles around the world used state-of-the-art emission controls

Figure 1.15 (Walsh, 1990)

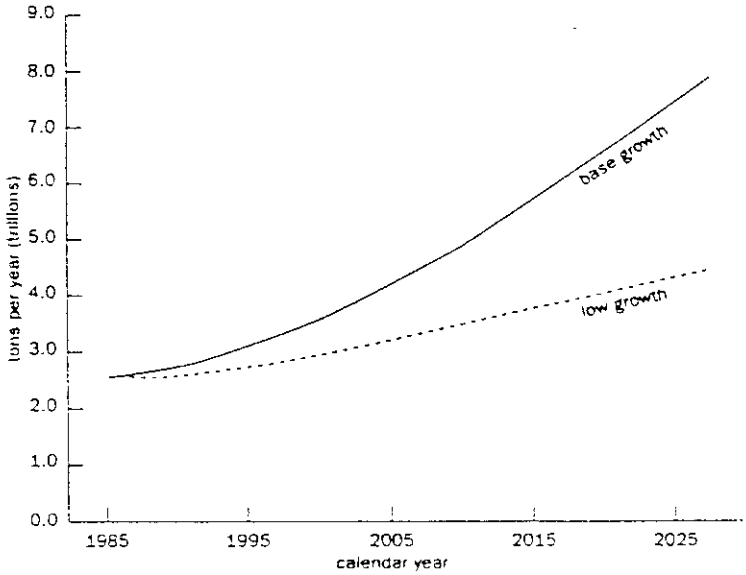


Trends in vehicle NO_x emissions by region if all vehicles around the world used state-of-the art emission controls

Figure 1.16 (Walsh, 1990)

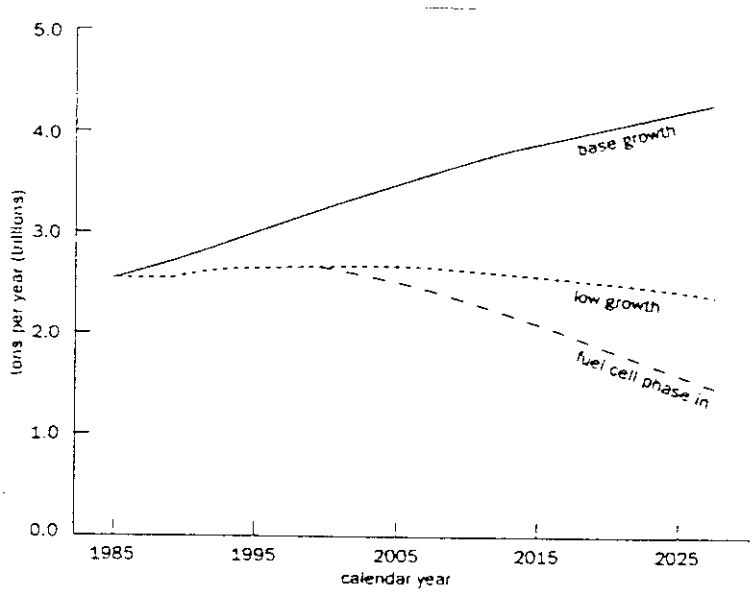
However, there are other improvements, such as to engine efficiency and new technology with cleaner or no exhaust gases which will significantly reduce emissions from transport vehicles. It has already been indicated that the use of fuel cells would significantly reduce emissions.

This thesis addresses the problem of reducing pollution from the transportation sector, but recognises that road congestion, particularly in city and urban areas, can only be relieved by reducing the total number of vehicles and improving and increasing public transport. Thus, in addition to considering clean technologies such as batteries and fuel cells for reducing pollution, the results are examined in the context of transport demand management and are applied to public transport systems, namely buses and railways.



Global vehicle CO_2 emissions assuming no improvements in vehicle efficiency

Figure 1.17 (Walsh, 1990)



Global vehicle CO_2 emissions assuming 2-per-cent annual vehicle-efficiency gain, showing impact of fuel cell phase-in

Figure 1.18 (Walsh, 1990)

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2. JUSTIFICATION AND METHODOLOGY

A simple philosophy to combat the impact of transport on the environment by converting all vehicles to clean systems would do little to ease the current congestion on our roads; any new system would be better applied in the first instance to public and commercial transport rather than private vehicles. (Section 2.4, below).

2.1 INTRODUCTION

The main theme underlying the remainder of this thesis is the need to reduce the harmful emissions, in terms of both global warming and health hazards, from transport. Reductions in emissions from the transport sector could be made by:

(a) advanced exhaust emission control,

(b) increased energy efficiency such as increasing the efficiency of internal combustion (IC) engines or developing alternative technologies,

(c) using lower polluting or cleaner fuels than petroleum or diesel, for example natural gas,

(d) a fall in the use or numbers of cars; this would probably need both an improvement and an increase in the number of public transport vehicles.

The most practical effective approach is likely to involve a mixture of the above. However, in the past (eg in the USA) although increased efficiency and advanced exhaust emission control (catalytic converters) reduces emissions, increases in the use of traffic vehicles has resulted in an increased use of fuel and consequent pollution. Policies for the reduction of vehicle numbers have been investigated elsewhere eg (Hughes 1992), and is outside the scope of this thesis. To reduce pollution

significantly from the transport sector conceivably requires both a reduction in use and cleaner vehicles. This thesis considers the latter, taking into account the need to reduce vehicle numbers by applying the results to public transport systems. Also, a reduction in vehicle numbers, particularly on roads, is seen to be vital in reducing traffic congestion.

Thus, although cleaner technologies are vital, they cannot be seen as being a simple solution on their own. This thesis accepts this, but for practical considerations, concentrates on evaluating cleaner technologies, particularly the fuel cell (see next paragraph). Also, it considers the development of fuel cells in a way that could contribute to a strategy of managing transport demand by improving public transport technology.

The case for clean transport systems needs to address the environmental impacts at all stages; an environmental life cycle analysis is needed rather than simply an analysis of emissions during usage. Some work on this topic has been completed in the past and is considered later in paragraph 2.3. This thesis considers this aspect for selected public transport vehicles and for a number of fuels. However, before specific public transport vehicles are considered comparisons are made between IC engines, fuel cells and batteries.

Because they have the potential of providing vehicles with zero emissions, the most relevant of alternative technologies for transport are those which could be used in electric vehicles eg batteries, fuel cells and photovoltaic generators used for direct drive or battery charging. Batteries, as well as alternative fuels for IC engines, are already in use in vehicles, and both are currently less costly and easier to market than fuel cells. However, fuel cells are being widely considered to represent a key, long term clean technology for vehicles, particularly in conjunction with the use of hydrogen. Electric vehicles using fuel cells have been proposed to alleviate pollution from road transport systems, and several prototype programmes are underway, for example (MacKenzie, 1994), (Chalk and Patil, 1995), (Klaiber, 1995), (Prater, 1995). Details

of these and further examples, and of programmes using rechargeable battery systems, are given in chapter 6.

Before discussing past work and the major topics to be considered in this thesis in detail, some consideration is now given to the alternative technologies and their place in following chapters.

2.2 ALTERNATIVE TECHNOLOGIES

In addition to the electrical technologies mentioned above, the use of alternative fuels in IC engines can be used to reduce emissions and atmospheric pollution. Whilst this thesis concentrates on fuel cells, it compares their use with a number of alternative fuels that are being used, or could be used, in IC engines. However, as already expressed above, because of their potential to provide zero emission vehicles, the most relevant of the alternative technologies that could reduce transport pollution are those which could be used with electric drive vehicles, eg fuel cells, batteries or photovoltaic panels used for direct drive or battery charging. Electric vehicles are discussed later in chapter 6.

2.2.1 FUEL CELLS

Various types of fuel cells could be used for transport systems, ranging from operation at about $90^{o}C$ to $900^{o}C$.

In general, the advantages of fuel cell systems are that they have higher efficiencies and hence lower emissions than internal combustion engines. More importantly, if they operate on pure hydrogen as a fuel then the waste product is water. Fuel cells electro-chemically convert fuel directly into electrical energy and are discussed in detail in chapter 3. Fuels and fuel processing are discussed in chapters 4 and 5.

Past work on fuel cells for transportation applications is discussed in section 2.3, below.

2.2.2 BATTERIES

Various types of batteries could be used to power electric drives for transport systems, ranging from ambient temperature operation to those which require a high temperature of 300 to 350^{o}C. Ambient temperature batteries include lead acid, nickel/cadmium, nickel/iron, nickel/zinc and zinc/bromine, but the first two are the only currently available types. High temperature batteries include sodium/sulphur, sodium/nickel chloride and lithium aluminium/iron sulphide, but only the first two types are currently serious contenders. Batteries are described in more detail in Chapter 6.

2.2.3 SOLAR RADIATION

The conversion of solar radiation directly into electrical energy can be achieved by a number of types of photovoltaic cells normally connected into series/parallel modules:

(a) silicon cells in either monocrystalline, polycrystalline, thin film or an amorphous form,

(b) gallium arsenide cells, a compound semiconductor suitable for thin film technology with a crystal structure similar to that of silicon, but consisting of alternating gallium and arsenic atoms,

(c) copper indium diselenide, a semiconducting compound of copper, indium and selenide, suitable for thin film cells,

(d) cadmium telluride, a compound semiconductor of cadmium and tellurium, also suitable for thin film cells.

Photovoltaic panel systems have been used in a variety of applications; in transportation they have been used for battery charging, directly powering an electric car and an

electrically driven propeller assisted glider.

A slow speed, solar powered aircraft with photovoltaic panels providing power to 12 electrically driven propellers has been reported (Sunday Times, 1997). This aircraft is the quarter size prototype for a proposed, high altitude, solar powered aircraft as part of the NASA environmental research programme to monitor pollution and weather at high altitudes.

It is considered (PA Consulting Group, 1992) that, until manufacturing costs are reduced and efficiencies increased, photovoltaic technology is not a serious contender for general transportation applications. However, when combined with hydrogen production by electrolysis the technology could become an important factor in establishing a hydrogen economy.

2.3 PAST WORK ON STRATEGIC ISSUES

A literature search has been carried out dealing specifically with the strategic issues of applying fuel cells to transport rather than their technological aspects. It was aimed at providing a background to determine which topics require in-depth study and which could be included in the main part of the thesis. Strategic issues are seen as the advantages of using fuel cells with electric drive to replace conventional power units, where they can be most advantageously applied and logistics such as fuel manufacture and supply. The most obvious advantages are reductions in atmospheric pollution, fuel and energy consumption.

2.3.1 PAST WORK ON FUEL CELLS FOR GENERAL TRANSPORTATION

Over seventy papers concerning the application of fuel cells in land transportation published between 1979 and 1996 have been surveyed, some in abstract form (DOE, 1985). The earlier papers up to 1989/90 quote the need for future reductions in energy consumption and liquid petroleum as being the main reasons for alternative systems to internal combustion engines. Also, the majority of papers, although citing energy

saving and reduced emissions as the reasons for developing fuel cell power systems, mainly deal with the engineering and electrochemical aspects of applying fuel cells to transport vehicles and only superficially with strategic issues. Relatively few papers deal in any depth with strategic issues and inevitably with some repetition of particular issues addressed. The first of these appear in 1990 and consider mainly the potential reduction in global warming by using fuel cells for road transportation (Lemons, 1989), (Walsh, 1990), (Patil, 1992), (Patil et al, 1992).

Future predicted trends in motor vehicle global population growth, fuel efficiency and various motor vehicle emissions (HC, CO, and NO_x) as a result of currently adopted requirements are given by Walsh (1990). This paper has been discussed in chapter 1, but some of this discussion is repeated here for clarity. The above future predicted trends are compared with trends as a result of all vehicles using state-of-the-art emission controls. Also, it is shown that the dual goals of low emissions (HC, CO and NO_x) and improved energy efficiency (and hence lower CO_2) are both compatible and mutually reinforcing, but that sufficient gains in either area are dependent on forceful government requirements. The motor vehicle industry has been ineffective in adopting new pollution controls and governments reluctant to adopt stringent targets. Global emissions in CO_2 are given assuming:

(a) no improvements in vehicle efficiency,

(b) 2% annual gain in vehicle efficiency,

(c) 2% annual efficiency gain and phase in of fuel cell vehicles at the rate of 3% conversions per year.

If no improvements in vehicle efficiency are achieved, then a modest reduction in the global growth rate of vehicle miles results in CO_2 emissions continuing to rise but at a lower rate than the base rate, see Figure 1.17. The modest reduction in vehicle growth is defined by assuming a 1% to 2% reduction for individual continents or sub-continents, resulting in a drop from a base rate of 3.23% to 1.97%

An assumed 2% annual improvement in vehicle efficiency results in a gradual reduction in fuel consumption per year, but only after about 20 years, see Figure 2.1.

Only a combination of the above lower growth in the global motor vehicle population and miles driven, coupled with a 2% per year improvement in conventional new car efficiency and a 3% shift to fuel cells from the year 2000, are shown by Walsh to achieve a reduction in levels of CO_2 emission, see Figure 2.2.

Petroleum dependence and pollution reduction (mainly NO_x and CO_2) are given (Lemons, 1990) (Patil, 1992a) and (Roan, 1992) as motivations for exploring the potential for fuel cell transportation applications. Fuel cells produce negligible amounts of NO_x (particularly those operating at low temperature), lower levels of other pollutants and particulates than internal combustion (IC) engines, are intrinsically quiet and can provide at least twice the efficiency of IC engines.

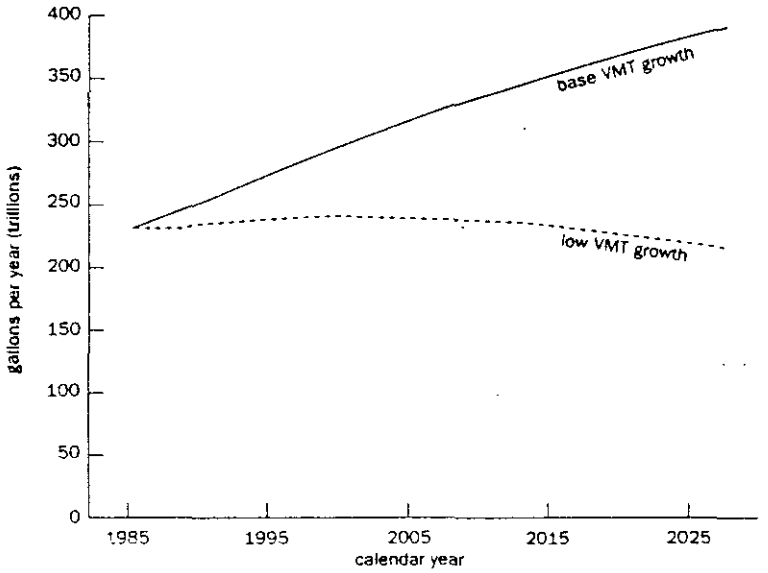
Predicted energy and economic benefits (Patil et al, 1992) based on the cost of fuel for fuel cell vehicles, the amount of displaced oil and the increased cost of vehicles, show that this extra vehicle cost offsets the gains from the energy benefits until the year 2011. Significant economic energy benefits are shown from the year 2012 up to 2030. These results are summarised in Tables 2.1 and 2.2, from Patil et al (1992), for methanol and hydrogen powered fuel cell vehicles.

TABLE 2.1

Year	Btu/mi	gNMVO/mi	gNOx/mi	gCO/mi	gCO2/mi	gCH4/mi
2000	3747	0.20	0.76	0.14	395.8	0.45
2010	3095	0.16	0.63	0.11	326.9	0.37
2020	2524	0.13	0.52	0.09	266.6	0.30
2030	2085	0.11	0.43	0.08	220.3	0.25

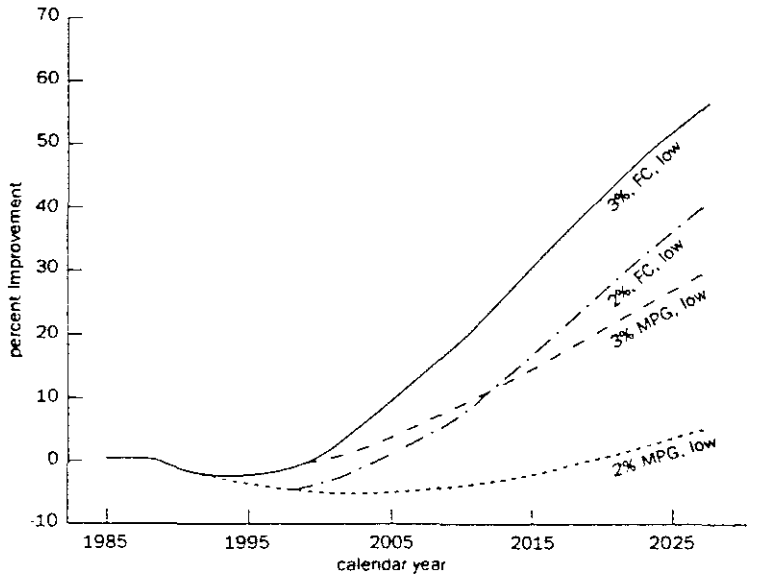
TABLE 2.2

Year	Btu/mi	gNMVO/mi	gNOx/mi	gCO/mi	gCO2/mi	gCH4/mi
2000	2817	0.07	0.65	0.09	331.6	0.76
2010	2327	0.05	0.54	0.08	237.9	0.63
2020	1897	0.04	0.44	0.06	223.4	0.51
2030	1568	0.04	0.36	0.05	184.6	0.42



Global vehicle fuel consumption assuming 2-per-cent annual vehicle-efficiency gain

Figure 2.1 (Walsh, 1990)



Global vehicle CO_2 emissions in the different scenarios used in this chapter, as a percentage improvement from 1985 performance

Figure 2.2 (Walsh, 1990)

Papers on fuel cells for public transportation first appear in significant numbers in 1990, (Abens, Chi and Glenn, 1990), (Kevala, 1990), (Romano, 1990), (Ross, 1990), (Kevala, 1992), (Mikoryak,1992), (Van den Broeck et al, 1992), (Werth and Kaufman, 1992), (Yamamoto, Tajima and Ohga, 1992) and (Prater, 1995). However, these mainly consider technological aspects and only two deal with strategic aspects.

The first, a study for a 30 to 40 foot long bus (Kevala, 1990) considers that, based on a production volume of 10,000 fuel cell units per year, the sale price of a fuel/ cell/battery bus is estimated to be $153,000, compared to $140,000 for an equivalent diesel engine vehicle. Life cycle costs for a fuel cell bus using an assumed methanol subsidised price of $0.50 per gallon compare favourably with life cycle costs for a diesel bus with a fuel cost of $1.00 per gallon. A production volume of 10,000 fuel cell units per year may be needed to justify the investment for a manufacturing facility. Thus, the fuel cell systems must be adaptable to other applications.

The second, (Mikoryak, 1992) concludes that the heavy duty transit bus has several unique characteristics making it a market entry choice, purchased at a ratio of about 10 to 1 over other size transit bus categories. However, these characteristics include a US federal funding subsidy, currently 80%. High passenger capacity transit buses are the alternative for city transportation to address the problem of traffic congestion.

2.3.2 PAST WORK ON ENVIRONMENTAL IMPACTS

Other studies have considered the total environmental impacts of new technologies and fuels for transport vehicles in the past, and background information of those in the USA has been obtained from DeLuchi, (1991). The first analysis (White, 1980) concluded that most alternative fuels for engines resulted in greater emissions of CO_2 from the production and usage than from petroleum. Later, in 1985, interest in alternative transport fuels was renewed, particularly in California. Emissions from the use of methanol (MacKenzie, 1987) and (Gushee, 1988), and amounts of

CO_2-Equivalent emissions from CO_2, CH_4 and N_2O (DeLuchi, Johnston and Sperling, 1987) were estimated. It was concluded that natural gas gave somewhat lower emissions than petroleum fuels; electric vehicles using electricity from the current mix of generators in the USA for battery charging gave about the same emissions as petroleum fuels; and methanol, electricity or hydrogen from coal gave much higher emissions than petroleum fuels.

Also in the USA, studies have been carried out by DeLuchi et al and the latest of these (DeLuchi, 1991) concluded that although CO_2 accounts for most of the total greenhouse gas emissions from transport and electricity, other gases (CO, CH_4, N_2O, NO_x and NMVOCs) are as, or more, important. Other conclusions were that large, long-term reductions in CO_2-Equivalent emissions from transport could be best achieved by using fuels derived from biomass or non-fossil derived electricity to charge battery vehicles or to produce hydrogen for internal combustion engine vehicles or fuel cell vehicles.

The above studies, in considering pollutants other than CO_2, have converted the results to CO_2-Equivalents according to the IPCCs 1990s estimates (IPCC, 1990) *Global Warming Potentials* or GWP of the indirect effects of greenhouse gases. *A GWP is a number that converts a mass-unit emission of a greenhouse gas other than CO_2 into the mass of CO_2 that has an equivalent warming effect over a given period of time*, (DeLuchi, 1992). In his previous report (DeLuchi, 1991) the IPCC 1990s estimates for GWPs were used for the 20, 100 and 500 year time horizons. However, it has been pointed out (DeLuchi, 1992) that later uncertainties about GWPs (IPCC, 1992) affects how the results should be interpreted. They should now be interpreted as *the outcome of making a particular set of assumptions about what the GWPs might be. The "time horizons" no longer necessarily represent time horizons, but rather general scenarios for, or assumptions about, the GWPs.*

In the UK, the first main study was carried out for The Department of Trade and Industry (PA Consulting Group, 1992). This was done for one particular type of

vehicle, a small car, and used data from DeLuchi, (1991) which already had been converted into CO_2-Equivalent emissions. The main findings were that battery powered retrofitted vehicles have an overall environmental impact comparable to that of internal combustion engine vehicles; battery powered retrofitted vehicles can become commercially viable in the context of a carbon tax scenario; purpose designed and built electric vehicles would be even more attractive; and from an environmental point of view, fuel cells are the most attractive option.

One European paper has been found (Klaiber, 1995) which quotes data for CO_2 emissions from different vehicle fuels tested in a simulation; petroleum, diesel, natural gas and hydrogen internal combustion engines, hydrogen and methanol fuel cells and $NaNiCl_2$ and NiCd batteries using one motor driving power of 37 kW.

Preliminary results from the earlier studies for the present thesis (Adams, 1996a, 1996b) compare total (manufacture plus usage) carbon dioxide emissions from IC engines and fuel cells for various fuels (petroleum, diesel, methane, propane, methanol, ethanol and hydrogen). These results have been updated in chapter 7 of this thesis, using later data for emissions produced during fuel manufacture. For fuel cell systems, the hydrocarbon and alcohol fuels are assumed to be steam reformed to produce hydrogen and carbon dioxide as the fuel. Although at the present day reforming systems are still to be developed for some of the fuels, particularly for use on-board transport vehicles, they are included for completeness. In these papers, CO_2 emissions from fuel manufacture are derived from published data (IPCC, 1991), (Klaiber, 1995), (Boustead and Hancock, 1979), (Legget, 1990) and (Deluchi, 1993). Emissions from IC engine vehicles also are from published data (IPCC, 1991). Results are given in terms of kg per kWh of energy generated by the fuel cell system or IC engine, against efficiency. Conclusions are that fuel cells operating at an efficiency of below about 40% and using reformed diesel or reformed petroleum produce CO_2 emissions comparable with IC engines using petroleum, propane or methane; those using reformed methanol or reformed ethanol produce CO_2 emissions comparable with IC engines using diesel, methanol, or ethanol. At higher efficiencies, the CO_2

emissions from fuel cell systems are significantly lower (about 50%) than from IC engines. The use of methane and propane reduce CO_2 emissions by about 20% when used in place of diesel in IC engines. They also produce the least CO_2 from fuel cell systems when compared with the other hydrocarbons and alcohols. In the possible build up to using hydrogen as a clean transport fuel, diesel fuel with an on-board reformer would be a good compromise. Later, and as a first transition, when on-board hydrogen storage is acceptable, the reformer could be transferred in a larger form to the fuel outlet station. In the longer term, when hydrogen generated from renewable sources is economical, it could be delivered directly to the fuel outlet station.

A later study (Gover et al, 1996) carried out for the Department of Trade and Industry and the Department of Transport is a preliminary life cycle study, in terms of both environment and cost, of alternative transport fuel for a number of road vehicle types using IC engines or electric drives using batteries. It considers the relative merits of petrol, diesel, liquefied petroleum gas, compressed natural gas, electricity, biomethanol, bioethanol and biodiesel fuels. Results are given in terms of energy use and emissions per gigajoule of fuel for fuel production, and in terms of energy use and emissions per kilometre for vehicle use. It concludes that, although demand for cleaner, alternative fuels could be enhanced by fiscal or regulatory measures stimulating low emission bus, freight and utility service vehicles in urban areas, *petrol and diesel will remain the major fuels for the foreseeable future.*

Another European paper (Hormandinger and Lucas, 1996) explores the environmental costs on the economic assessment of fuel cells in transport applications by setting a model of an urban bus fleet. It concludes that the private costs of a fuel cell bus exceeds that of its diesel equivalent by 23% to 33%, depending on size; the social costs are 89% to 95% of that of the diesel, insufficient to make a good case for the fuel cell. Thus, for fuel cells to enter the transport market they have to become more competitive in terms of private costs. Emission parameters for the fuel supply chain used in the model again use data from (DeLuchi, 1991) for the greenhouse gases which are in terms of CO_2-Equivalent.

2.3.3 KEY CONCLUSIONS

The literature search has dealt specifically with the strategic rather than technological aspects of the application of fuel cells to transportation. Main conclusions from this search are as follows:

(a) the introduction of fuel cells in transportation would slow down the current trends of increasing emissions and consequent global warming,

(b) the use of fuel cells would improve energy efficiency resulting in reduced fuel consumption,

(c) a combination of lower emission vehicles such as fuel cells, increased efficiency, a reduction in the global motor vehicle population and distance driven is needed to achieve a reduction in levels of CO_2 emission,

(d) increased public transport is needed to reduce traffic congestion,

(d) to enter the transport market the cost of fuel cells need to become more competitive,

(e) studies on the environmental impacts of low pollution transport options, particularly fuel cells, in terms of absolute units rather than CO_2-Equivalents are needed.

2.4 WORK PROPOSED FOR THIS THESIS

The present study is aimed at the potential for the application of fuel cells to transportation. The following topics are identified as those which have not received

sufficiently wide attention in the past and could be included in the main part of this study:

1. Identify appropriate types of conventional transport to compare with fuel cell systems whilst giving consideration to those types which would give the most benefit if powered by fuel cells.

2. Consider fuels for use with mobile fuel cell systems, particularly in terms of the infrastructure required for safe delivery to individual vehicles.

3. Calculate or reassess energy used for different fuels in engines and fuel cells, including both manufacture and usage of fuels, and compare with that for re-charging batteries.

4. Calculate or reassess the environmental impacts in terms of mass of pollutants for different fuels in engines and fuel cells including both manufacture and usage of fuels, and compare with that for re-charging batteries.

5. Environmental through life study of a selected urban transportation vehicle, using various fuels in engines or fuel cells and batteries, particularly in terms of atmospheric pollution at all stages such as manufacture, fuel production, infrastructure for fuel supply, and vehicle running.

6. Consider the effect of introducing fuel cell powered public transport on an urban and a city environment. This includes the possibility of employing fuel cell power generation stations to provide the recharging energy for battery driven vehicles.

7. Consider the effect of introducing fuel cell powered vehicles for rail transport. This includes the possibility of employing fuel cell power generation stations to provide the energy for overhead cable systems.

8. Consider the implications which the results of studies on the above three topics might have on future transportation systems, with particular regard to how fuel cell systems might be introduced in the future.

In selecting the appropriate types of land transport for fuel cell application, thought needs to be given to the necessity to reduce numbers of vehicles and the impact of any new infrastructure as well as to reduce atmospheric emissions. A simple philosophy to combat the impact of transport on the environment by converting all vehicles to clean systems would do little to ease the current congestion on our roads, particularly in the UK; any new system would be better applied in the first instance to public and commercial transport rather than private vehicles.

There is a need to manage the volume of road traffic as well as emissions from vehicles, otherwise increases in the former could overwhelm improvements in the latter. However, it is recognised that the management of traffic volume is difficult and involves policy actions at local, national and international levels. Changes in the fiscal arrangements relating to company cars (Potter 1992a) and to the assessment of public transport schemes have been proposed. Policies for cleaner vehicles have to be developed in conjunction with those for managing volumes of traffic, but the former is the focus of this thesis. Given this focus, the thesis does however explore the scope for introducing cleaner technologies in a way that enhances the performance of public transport vehicles. This includes the use of cleaner fuel cell electric power generation stations to recharge battery driven vehicles or to provide energy to vehicles via overhead cables or electric rails, thus assisting in enhancing the use of cleaner technologies as part of a portfolio for traffic management.

Emissions can be broadly divided into those which affect global warming and local air quality impacts, which are injurious to health; some materials may fall in both categories, and those injurious to health tend to have more effect in heavily populated areas. Thus, in the context of the present study, emphasis is placed on urban/city

transport. Also, the results, in terms of kg of pollutant per kWh of power system energy, are applicable to other transport systems.

The introduction of a fuel cell transport system would require a new fuel, hydrogen being preferable. However, the supply to, and the storage of hydrogen on board, road vehicles, may pose severe problems and an alternative fuel with on board reforming to produce hydrogen may need to be considered. Consequently, and particularly if hydrogen is to be used, it might be preferable to have a single storage and supply facility in any particular area rather than garage outlets as at present for petrol and diesel. This lends itself to a public transport system rather than private vehicles.

To avoid the potential difficulties of using CO_2-Equivalents derived using GWPs, section 3.4 above, and because the health effects of pollutants other than CO_2 are now considered to be of at least equal importance to global warming, this thesis presents results in terms of mass values for each pollutant. Additionally, the environmental effects of using what are considered to be the most likely options for fuels are reassessed. These fuels are considered for both internal combustion engines and fuel cells, and are compared with the environmental effects of re-charging battery vehicles.

Several fuel cell manufacturers were contacted for detailed information on performance and manufacture. However, the response was disappointing perhaps understandably because of obvious competition between different types and different methods of manufacture. The only information available was that obtained earlier for studies on marine applications (Adams, 1989, 1991, 1992), and out of date. Consequently, specific fuel consumption in mass of fuel per kilowatt-hour of energy output have been calculated for a range of efficiency from fuel data and, in the case of engines, found to agree with known data.

For the part of this study dealing with the calculation and re-assessment of data on energy used and pollution produced during the manufacture and usage of various fuels, results are presented as energy or mass of pollutant per kilowatt-hour of energy

developed by each power unit, against efficiency. This affords the advantage that the results are applicable to any fuel cell system, whether it be for transportation or power generation, provided either the fuel consumption or efficiency is known. Also, to compare different systems such as engines and fuel cells, the operating conditions must be clearly defined and be the same for each. This presents difficulties in ensuring that the vehicle performance, range, driving cycle, payload etc are identical, especially when one considers that different fuel systems will have different storage volumes and weights. Presentation of the results in terms of mass per kilowatt-hour of energy developed by a particular system overcomes these difficulties.

Also, results are calculated in terms of mass per kW using average speeds and driving cycles from published data (IPCC, 1991, 1995) and (Gover et al, 1996), and assuming a system lifetime. Thus, once the power output from a particular system is known results in terms of unit or total, distance travelled, may be calculated. The environmental through life study uses this type of calculation and assumes efficiencies for the engine and fuel cell systems.

Details of the methodology used in the calculations and estimates are given in the individual chapters (7,8 and 9) on the above topics numbered 1 to 7. Other chapters (3 to 6) include summaries on fuel cells, fuels, fuel processing, batteries and fuel cell electric vehicles. Each of these chapters is a review and analysis of relevant information on topics which are considered to be key subject headings for this research project.

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3. FUEL CELLS

As the chemical or catalytic action ... could only be supposed to take place, with ordinary platina foil, at the line or water-mark where the liquid, gas and platina met, the chief difficulty was to obtain anything like a notable surface of action. I determined to try platina platinized ... It is obvious that, allowing the platina to touch the liquid the latter would spread over its surface by capillary action and expose an extended superficies to the gaseous atmosphere

(W R Grove (1843) on the necessity for a *notable surface of action* between gas, electrolyte and electrode in a fuel cell).

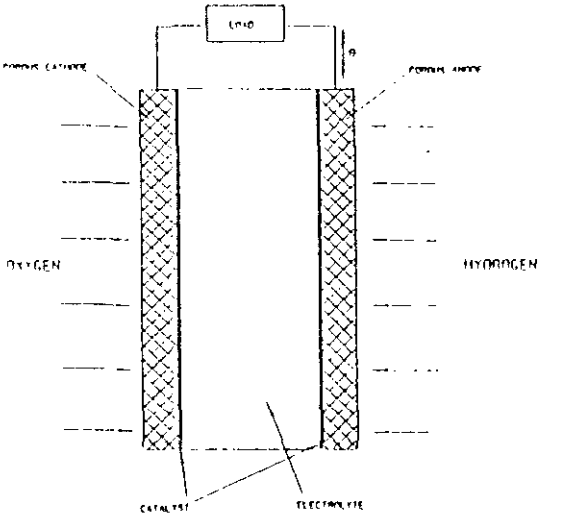
3.1 INTRODUCTION TO FUEL CELLS

A fuel cell is an electro-chemical power source which converts chemical energy in the form of fuel directly into electrical energy. However, unlike other electro-chemical power sources such as batteries which store their reactants within a cell, the reactants are fed continuously to it from external stores. Also, the electrodes in a fuel cell are not consumed as in a battery, irreversibly in a primary cell and reversibly in a secondary cell, and do not take part in the reaction. The electrodes serve to bring the reactants into contact with the electrolyte and support catalysts, normally platinum, to stimulate the reaction. Since the reactants are stored outside the cell the endurance of operation is limited by the amount of reactants stored and the equivalent of battery charging is replenishment of the stores.

Because fuel cells convert the reactants directly to electrical energy without combustion and heat transfer, the limitations of the Carnot cycle do not apply. The Carnot cycle is the cycle of reversible operations that the working substance of a heat engine undergoes to obtain the greatest possible amount of work. This leads to a limiting efficiency for a reversible heat engine of $(T_1-T_2)/T_1$, where T_1 and T_2 are

the temperatures of the engine heat source and sink, respectively. For any heat engine, this may be written as $(Q_1-Q_2)/Q_1$, where Q_1 is the heat taken in by the engine from the source at T_1, and Q_2 is the heat rejected to the sink atT_2. In practice, heat engines are not truly reversible and hence fall short of this limiting efficiency. In a fuel cell, loss of efficiency is due to the irreversibility of the entropy change (see section 3.3.5, later), electrode polarisation and ohmic resistance, resulting currently in overall efficiencies of between 45% and 65%.

In the simplest fuel cell, Figure 3.1, the reactants, hydrogen and oxygen, are separated by an electrolyte which is permeable to charged ions. Electrodes, in contact with either one or other of the reactant gases and the electrolyte, are porous to the gases and allow electron transfer, as well as supporting catalysts to stimulate the reactions.



Simplified Fuel Cell.

Figure 3.1

Adams (Unpublished)

The operation is best illustrated by considering the chemical reactions in an alkaline or acid electrolyte cell using hydrogen and oxygen. In an alkaline cell hydroxyl OH^- ions are formed at the cathode which then migrate to the anode where they react with hydrogen to form water and release free electrons. These electrons flow through the external load from anode to cathode to take part in a reaction to produce the hydroxyl ions. Reactions are:

$$2H_2 + 4(OH)^- = 4H_2O + 4e^- \text{ at the anode} \quad [1]$$

$$O_2 + 2H_2O + 4e^- = 4(OH)^- \text{ at the cathode} \quad [2]$$

resulting in an overall reaction of:

$$2H_2 + O_2 = 2H_2O \quad [3].$$

In an acid cell free electrons and positively charged hydrogen H^+ ions are formed at the anode. These ions migrate to the cathode where they react with oxygen to form water. This reaction is completed by the electron flow through the external load from anode to cathode. Reactions are:

$$2H_2 = 4H^+ + 4e^- \text{ at the anode} \quad [4]$$

$$O_2 + 4H^+ + 4e^- = 2H_2O \text{ at the cathode} \quad [5]$$

resulting in an overall reaction of:

$$2H_2 + O_2 = 2H_2O \quad [6].$$

Molten carbonate electrolyte fuel cells operate at a much higher temperature, circa 600 ^{o}C, than the above types and the ionic conduction is by the transport of the CO_3^{2-} carbonate ion, which is consumed at the anode and regenerated at the cathode:

$$H_2 + CO_3^{2-} \text{ ---> } H_2O + CO_2 + 2e^- \quad [7] \text{ at the anode}$$

$$1/2O_2 + CO_2 + 2e^- \text{ ---> } CO_3^{2-} \quad [8] \text{ at the cathode}$$

$$\text{resulting in } \quad H_2 + 1/2O_2 \text{ ---> } H_2O \quad [9].$$

To give the best performance consistent with properties of materials, this type is usually operated at about 650^{o}. One major advantage is that they can consume carbon monoxide and carbon dioxide contained in fuels such as reformed natural gas or gasified coal.

Solid oxide electrolyte fuel cells, based on stabilised zirconia (ZrO_2) or ceria (CeO_2), operate at even higher temperature, circa 1000 ^{o}C, and the ionic conduction is by the transport of O^{2-} oxide ions:

$$1/2O_2 + 2e^- \text{ ---> } O^+ \text{ at the cathode} \quad [10]$$

$$H_2 + O^{2-} \text{ ---> } H_2O + 2e^- \text{ at the anode} \quad [11]$$

resulting in

$$H_2 + 1/2O_2 \text{ ---> } H_2O \quad [12].$$

Solid oxide electrolyte fuel cells can also use carbon monoxide as a fuel since, whilst there is some tendency for a shift reaction in the presence of water vapour to convert carbon monoxide to carbon dioxide and hydrogen,

$$CO + H_2O \text{ ---> } CO_2 + H_2, \quad [13]$$

it can also be used in a direct anode reaction to produce carbon dioxide and free electrons,

$$CO + O^{2-} \text{ ---> } CO_2 + 2e^- \quad [14].$$

A single cell produces about 1 volt or less and so in practice a number of cells are connected in series and built into units or stacks, using a sandwich construction. Ancillary equipment for water removal, cooling, fuel and oxygen feed, pressure balancing, shut down and if necessary, inert gas purge also are required and normally provided for each cell stack which may have a total power output of 5 kW to 100s of kW depending upon the type of cell and application. In order to build practicable larger scale systems, banks of stacks are used in series/parallel arrangements with controls and monitoring equipment shared amongst a number of individual stacks and cells. Depending upon the application and redundancy required it is possible that the ancillaries could be shared between a number of stacks.

3.2 HISTORY OF FUEL CELLS

The invention of the fuel cell dates from Sir William Grove's gaseous voltaic cell of 1839 (Grove, 1839) and later (Grove, 1874) he describes cells operating on different reactants including hydrogen, ethylene and carbon monoxide. The first fuel cell (Grove, 1839) consisted of hydrogen and oxygen in contact with two platinized electrodes, and Grove also described the possibility of fifty of these cells to form a gaseous voltaic battery (Grove,1843). The performance of Grove's cells in terms of delivering current to an external circuit, were limited by the small effective electrode area of approximately 10 mm^2, effected by a meniscus about 2 mm high on a platinized platinum about 6 mm wide. Grove also recognised the need for a high area of contact between the electrolyte, the gaseous reagents and the electrocatalytic

conductor, *a notable surface of action*, ((Grove, 1843) and quotation at heading of this chapter). Attempts to an obtain an optimum, maximum reaction surface have occupied researchers and developers of fuel cells ever since.

The concept of increasing the surface of action was first explored (Mond and Langer,1889) by using a three dimensional porous electrode structure and rotating the structure through 90 degrees, thus making a cell with features similar to that of the modern fuel cell. Each electrode consisted of a porous diaphragm (eg plaster of Paris) with perforated platinum or gold leaf as the conductor with catalytic surfaces of platinum black. The porous diaphragms were in contact with the reactant gases and the electrode structures could be placed side by side or one above the other. These cells operated on hydrogen and oxygen at 0.73 volt and a current density of 3.5 mA/cm^2. Modern fuel cells use porous electrodes, thin diaphragms carrying the electrolyte and operate at current densities up to 1000 ma/cm^2.

Mond and Langer also advocated coal as a source of hydrogen and this was first demonstrated (Jacques, 1896) in a 1.5 kW system with 100 cells consisting of iron tubes as cathodes with internal fuel rods made of coke. The electrolyte was molten potassium hydroxide at about $450^{O}C$ and air was used as the oxidant. A current density of 100 mA/cm^2 at 1.0 volt was obtained and cells were about 1.2 m high and 0.3 m in diameter. Jacques suggested the use of such cells for urban power generation and in an all electric ship. It was later (Haber and Brunner, 1904) shown that the reaction of the carbon with oxygen produced a carbonate, stopping the reaction. Jacques assumed that the waste nitrogen in the air would bubble through the electrolyte and remove the excess carbonate as carbon monoxide. However, after rapid neutralisation of the electrolyte the reaction stops and the electrolyte must be regenerated or replaced, which requires energy.

Attempts to use coal directly in a cell by using molten carbonates as the electrolyte, (Baur, 1910) and (Baur and Ehrenberg, 1912), failed due to low conductivity, the formation of ash and the need for continuous feed of the fuel. Later, Baur et al,

(1921) used gaseous reactants with molten carbonate electrolyte.

It was not until 1959, following on from work started in 1939, that the first practical fuel cell (5 kW) was successfully engineered by F. Bacon (Appleby, 1989) in the UK. A fully engineered system was later adopted in the USA as the basis of the NASA Apollo fuel cell programme and developed into units which proved successful for on-board power for space vehicles. The electrolyte was hot potassium hydroxide solution, circulated to remove heat and excess water, and the reactants pure hydrogen and oxygen. The electrode structure was porous and the electrolyte contained in a matrix powder material and a large surface of action obtained by capillarity; the range of pore diameter in the electrode overlapped that in the electrolyte matrix so that fine pores are filled with electrolyte and coarse pores are filled with the reactant gas, giving a large surface area for the reaction.

Since the successful use of fuel cells in space applications, there has been significant development with several land power generator demonstrators ranging from small combined heat and power units of 40 kW output to large systems with over 11 MW output, eg see Itoh (1989) and Sugimoto et al (1992). Small systems of power levels up to about 100 kW have been demonstrated in underwater vehicles. A fuel cell power generator system includes equipment other than the fuel cell itself, which is the dc power unit containing the stacked cells. Complete systems include peripherals, the integration of which is as important a factor as the fuel cells, to produce hydrogen from a primary fuel, handling of waste water and gas and conversion from dc to ac for most users. Vehicles have the advantage of potentially being driven by dc electric motors and thus not requiring converters.

In the present development phase of fuel cells, emphasis is being placed on engineering and on their low impact on the environment. However, fuel cells are currently significantly more expensive than internal combustion engines and gas turbines. Their construction involves elements which are built by hand, and they will not become competitive until demand requires mass production. The future use of

fuel cell systems probably hinges on the implications of stricter legislation for conventional stationary power plants and vehicles, when it could become a competitive option by supply having to meet demand.

This chapter began with the statement that fuel cells operate electro-chemically, and not subject to the efficiency limitations of heat engines dictated by the Carnot cycle. To understand more fully the operation of fuel cells, the following section (based on Oniciu, (1976)) considers their thermodynamics and calculates the theoretical voltage, heat generated and efficiency.

3.3 THERMODYNAMICS OF FUEL CELLS

3.3.1 FREE ENTHALPY OF REACTION

The overall chemical reaction of a fuel cell is given in equation [3], section 3.1, above. The complete thermodynamic equation, including the emf, operating temperature and heat exchanged for a single cell is:

$$2H_2 + O_2 = 2H_2O + zFE - Q + 3RT \quad [15]$$

where F is Faraday's number, z is the number of electrons involved in the reaction, E is the emf of the cell, Q is the heat exchanged with the environment, R the Gas constant and T the temperature. If n_i is the number of molecules of reactants and M_i the various chemicals involved, so that $M_1 = H_2$, $M_2 = O_2$, $M_3 = H_2O$, $n_1 = 2$, $n_2 = 1$ and $n_3 = -2$, then:

$$n_iM_i = zFE + Q + W \quad [16]$$

where W is the work and zFE is the electrical energy exchanged with the environment, respectively. If U_i is the internal molar energy of the chemicals M_i, then by the law of conservation of energy:

$$\mathrm{Sum_i\{n_i U_i\}} = zFE + Q + W \quad [17]$$

This equation indicates that the energy of the reaction is dissipated as heat and electrical energy.

The work may be defined by:

$$W = \mathrm{Sum_i\{p_i DV_i\}} \quad [18]$$

where D is the change in volume of M_i during the reaction and V_i is the molar volume at partial pressure p_i and temperature T, and thus:

$$\mathrm{DV_i} = \mathrm{- Sum_i\{n_i V_i\}} \quad [19]$$

and the work, W becomes:

$$W = \mathrm{- Sum_i\{n_i p_i V_i\}} \quad [20].$$

If the molar entropy of M_i is S_i at P_i and T, the entropy of the reaction is DS_1 and the entropy change of the surroundings is DS_2, then the total entropy change, DS, is the sum of DS_1 and DS_2:

$$\mathrm{DS_1} = \mathrm{- Sum_i\{n_i S_i\}} \quad [21],$$

$$\mathrm{DS_2} = Q/T \quad [22],$$

and:

$$DS = \mathrm{DS_1 + DS_2} = \mathrm{- Sum_i\{n_i S_i\}} + Q/T \quad [23]$$

which is greater than, or equal to, zero.

Thus,

$$- T \, Sum_i\{n_i S_i\} + Q \; > \text{or} = 0 \quad [24].$$

Substituting equations [17] and [18] in [24]:

$$-T \, Sum_i\{n_i S_i\} + Sum_i\{n_i U_i\} + Sum_i\{n_i p_i V_i\} - zFE \; > \text{or} = 0 \quad [25]$$

or,

$$zFE \; < \text{or} = \; Sum_i\{n_i(U_i + p_i V_i - TS_i)\} \quad [26].$$

If the reaction is reversible the inequalities in the above become equations. The sum in equation [26]:

$$Sum_i\{U_i + p_i V_i - TS_i\} \; = \; Sum_i\{n_i G_i\} \quad [27],$$

is the variation in free enthalpy, -DG, in the reversible reaction and is equal to the electrical energy supplied by the fuel cell. Thus, substituting equation [27] in [24] gives:

$$zFE \; < \text{or} = \; Sum_i\{n_i G_i\} \quad [28]$$

or,

$$E \; < \text{or} = \; - DG/zF \quad [29]$$

which gives the limiting value of the EMF as a function of the change in free enthalpy

during the reaction. The energy released also may be expressed in terms of the enthalpy, H = U + pV and thus, from equations [17] and [21]:

$$zFE + Q = Sum_i\{n_i(U_i + p_{ii})\} = Sum_i\{n_iH_i\} \quad [30]$$

and combining equations [28] and [30]:

$$Q > \text{or} = Sum_i\{n_i(H_i - G_i)\} \quad [31].$$

3.3.2 THEORETICAL EMF AND HEAT GENERATED

From the above it is possible to calculate the theoretical EMF and heat generated by a fuel cell using hydrogen and oxygen.
Assuming 25^{O}C and 1 atmosphere, the changes in the enthalpy and free enthalpy for the reaction $H_2 + 1/2O_2 = H_2O$ are:

$$DH^{O} = - Sum_i\{n_iH^{c}_i\} = - 68.25 \text{ kcal/mol}$$

and

$$DG^{O} = - Sum_i\{n_iG^{O}_i\} = - 56.7 \text{ kcl/mol.}$$

Thus, the EMF of the cell is:

$$56.7*4.18/96.5*2 = 1.23 \text{ volt}$$

and the heat evolved is:

$$- 68.5 + 56.7 = - 11.55 \text{ kcal/mol.}$$

3.3.3 Variation with Temperature and Pressure

For a perfect gas, the free enthalpy, or Gibbs free energy:

$$G = U + pV - TS = H - TS \qquad [32]$$

and only D variations of U, H and S can be measured between a reference temperature and the temperature of interest. Assuming that the reactants are perfect gases, liquids or solids (the volumes in the condensed state are negligible compared with the gas volume) and the molar heat capacities, C_p are constant, then:

$$DH = DU + D(pV) = C_v DT + D(RT) = (C_v + R)DT = C_p DT \qquad [33]$$

If X^O denotes the quantities at the reference state, then:

$$DH = H - H^O = C_p(T - T^O) \qquad [34]$$

and the entropy variation is:

$$TdS = dU + pdV = d(U + pV) - Vdp = dH - Vdp = C_p - Vdp \qquad [35].$$

For a gas:

$$dS = C_p.dT/T - R.dp/p \qquad [36]$$

and

$$DS = S - S^O = C_p.\ln(T/T^O) - R.\ln(p/p^O) \qquad [37].$$

For condensed states:

$$dS = C_p.dT/T \qquad [38]$$

and

$$DS = S - S^O = C_p.\ln(T/T^O) \qquad [39]$$

From equations [37] and [38]:

$$TS - T^OS^O = C_pT.\ln(T/T^O) - [RT.\ln(p/p^O)]_g + S^O(T - T^O) \qquad [40]$$

where the term in square brackets refers to gaseous species.

Now,

$$DG = G - G^O \qquad [41]$$

and from equations [34] and [40]:

$$DG = (C_p - S^O)(T - T^O) - C_pT.\ln(T/T^O) + [RT.\ln(p/p^O] \qquad [42].$$

Thus, for all the reactants,

$$Sum_i\{n_iG_i\}-Sum_i\{n_iG^O_i\} = (Sum_i\{n_iC_{p,i}\}-Sum_i\{n_iS^O_i\})(T-T^O)-(Sum_i\{n_iC_{p,i}\})T.\ln(T/T^O)+RT.Sum_i^g\{n_i.\ln(p_i/p^O_i)\} \qquad [43]$$

where the final Sum_i^g refers to gaseous species. The value of S_i may be obtained from:

$$Sum_i\{n_iS_i^O\} = 1/T_O(Sum_i\{n_iH^O_i\} - Sum_i\{n_iG^O_i\}) \qquad [44].$$

The EMF temperature variation may be calculated from the Gibbs-Helmholtz equation:

$$E - T(dE/dT)_p = 1/zF.Sum_i\{n_iH_i\} = E_{100\%} \quad [45]$$

where $E_{100\%}$ is the EMF when the total energy released in the reaction is transferred into electrical energy. Using the figures obtained above in paragraph 4.2,

$$E_{100\%}*68.25*4.18/96.5*2 = 1.48 \text{ volt.}$$

Thus, from equation [45],

$$(dE/dT)_p = -(E_{100\%}-E_r)/T$$

$$= (1.48-1.23)/(273+25) = 0.84.10^{-3} \text{ VK}^{-1}.$$

3.3.4 FREE ENERGIES AND EQUILIBRIUM

Consider a system at uniform temperature T, separated from the surroundings by a wall allowing thermal exchange and with volumes V_i and pressures p_i on different parts of the wall. If S and U are the entropy and internal energy of the system, and DS, DU, Dp_i and DV_i are the increase of S, U p_i and V_i, the mechanical work done on the surrounding is $Sum_i\{p_iV_i\}$, and in addition, energy W, is released (eg electrical energy zFE). The heat exchanged with the environment is:

$$Q = DU + Sum_i\{n_iDV_i\} - W \quad [46].$$

The entropy of the surroundings decreases with Q/T and, according to the Second Law of Thermodynamics,

$$DS > \text{or} = Q/T \quad [47]$$

or,

$$DS - Q/T > \text{or} = 0, \quad [48].$$

Thus,

$$TDS > \text{or} = Q \quad [49]$$

and therefore,

$$TDS > \text{or} = U + \text{Sum}_i\{p_i DV_i - W \quad [50]$$

or,

$$-W < \text{or} = TDS - DU - \text{Sum}_i\{p_i DV_i\} \quad [51],$$

If the transformation is reversible, the inequality becomes an equation and:

(a) if $-W > 0$, the transformation is spontaneous and releases energy with a maximum value of W,

(b) if $-w < 0$, the transformation requires that an energy of at least W is supplied to the system,

(c) if $-W = 0$, the system is in equilibrium.

From (a), the reaction requires that the Sum in the right hand side of equation [51] decreases. Thermodynamic potentials for spontaneous reactions are shown in Table 3.1.

TABLE 3.1 THERMODYNAMIC POTENTIALS AND PARAMETERS

External Conditions	Thermodynamic Potential	Conditions
T and p constant	H - TS	-W < or = -DG = -D(H - TS)
T and V constant	U - TS	-W < or = -DF = -D(U - TS)
S and p constant	H	-W < or = -DH
S and V constant	U	-W < or = -DU
Adiabatic processes		DS > or = 0 (Q = 0)

If T and V are constant:

$$DV_i = 0 \quad \text{and} \quad TDS = D(TS) \qquad [52]$$

and equation [51] becomes:

$$W < \text{or} = D(TS - U) = -D(U - TS) = -DF \qquad [53].$$

If S and p_i are constant:

$$DS = 0 \quad \text{and} \quad p_i DV_i = D(p_i V_i) \qquad [54]$$

and equation [51] becomes:

$$W < \text{or} = -DU - \text{Sum}_i\{p_i V_i = -DH \qquad [55].$$

In general:

$$(DH)_{S,p} = (DU)_{s,v} = (DG)_{T,p} = (DF)_{T,V} \quad [56].$$

3.3.5 THEORETICAL EFFICIENCY

The theoretical efficiency may be calculated from:

$$\text{eff.} = W_{max}/DH = DG/DH = 1 - T.DS/DH \quad [57]$$

ie, from paragraph 3.3.2 above,

$$\text{eff.} = 56.7/68.25 = 0.831 \text{ or } 83.1\%.$$

However, in practice because of the irreversibility of T.DS, electrode polarisation and ohmic losses in the cell, efficiencies are between 45% and 65%. From equation [29] above, the electromotive force is:

$$E_r = - DG/zF = - (DH - TDS)/zF \quad [58]$$

where E_r represents the voltage of a reversible fuel cell which provides the maximum work M_{max}. The electrical work done on the external load is:

$$W_{el} = zFE_b \quad [59]$$

where E_b ($< E_r$) is the actual value of the potential drop, and the electrical efficiency is given by ratio of W_{el} and the change in enthalpy for the electro-chemical reaction, DH:

$$\text{Elec. eff.} = W_{el}/DH = \text{eff.}(W_{el}/W_{max}) = \text{eff.}(E_b/E_r) \quad [60]$$

The electrical efficiency also may be written as:

$$\text{Elec. eff.} = E_b/E_{100\%} \quad [61]$$

where

$$E_{100\%} = E_r/\text{eff.} = -DH/zF \quad [62]$$

is a theoretical value of the electromotive force, calculated when the reaction enthalpy is assumed to be entirely converted into electrical energy.

Finally, the energy dissipated as heat may be calculated from :

$$Q = -DH - W = (E^r-E^b)zF-TDH = -DH(1-\text{Elec. eff.}) \quad [63].$$

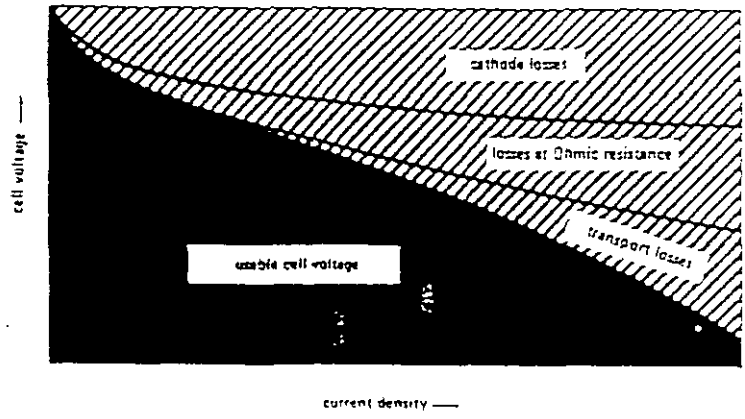
A schematic fuel cell voltage against current characteristic is given in Figure 3.2, which shows that the cell voltage decreases with increasing current. The Figure also illustrates that:

(a) losses at low currents are primarily due to polarisation of the cathode,

(b) ohmic resistance increases as current increases,

(c) transport losses are significant at the highest currents and negligible at normal operating levels.

All of the above losses are due to polarisation within the cell (Appleby and Foulkes, 1989). The cathode losses, due to *activation polarisation*, are related to the charge transfer reaction across the electrode-electrolyte interface, and result in a portion of the electrode potential being lost in driving the electron transfer rate to that required by the external electrical current demand. *Ohmic polarisation* results from electrical resistance losses within the cell, due to resistance (a) to ion transfer in the electrolyte, (b) ion and electron transfer in the electrodes and (c) of the terminal connections in the cell. The transport losses are due to *concentration polarisation*, caused by mass transport limitations on the reactant species (ions and electrons) at the electrode-electrolyte interfaces. These mass transfer effects are influenced by diffusion or convection limitations which reduce the availability of species, leading to reduced electrode activity and a corresponding loss in output voltage.



Inner losses of cell voltage (schematic).

Figure 3.2
Strasser (1989)

3.4 FUEL CELL TYPES

A number of fuel cell types have been developed or are under development, and are fully discussed in the literature (Appleby and Foulkes, 1989). The main types, described in section 3.1 above, are:

(a) Aqueous alkaline electrolyte, usually potassium hydroxide.

(b) Aqueous acid electrolyte, usually phosphoric acid.

(c) Proton exchange membrane or solid polymer acid electrolyte, an ionic conducting polymer membrane in the form of a flexible sheet, is a special case of the acid type.

(d) Molten carbonate electrolyte, which becomes conducting at a high temperature.

(e) Solid oxide electrolyte, usually an oxide of zirconia or ceria which becomes conducting at a high temperature.

In principle any fuel cell type could be used for transportation applications but important parameters in selecting a choice are power density and power per unit weight. Approximate values of these are given in Table 3.2 for fuel cell types which might well be developed for transportation use. Other criteria, such as operating temperature and whether proven in demonstrators or applications are given in Table 3.3.

TABLE 3.2 APPROXIMATE POWER DENSITIES AND POWER TO WEIGHT RATIOS OF FUEL CELLS

Fuel Cell Type	Power Density ($kW.m^{-3}$)	Power/Unit Weight ($kW.kg^{-1}$)
Proton Exchange Membrane (PEMFC)	250 to 1000	0.5 to 1.3
Alkaline (AFC)	100 to 200	0.02 to 0.1
Phosphoric Acid (PAFC)	100 to 160	0.05 to 0.1
Molten Carbonate (MCFC)	100 approx.	0.1 approx.
Solid Oxide (SOFC)	1 to 100 (conceptually >2000).pa	

TABLE 3.3 CURRENT STATE OF FUEL CELL DEVELOPMENT

TYPE	TEMP (^{o}C)	EFFICIENCY (%)	STATUS	REMARKS
AFC	70-90	50	100 kW stack tested	Submarine Space and Traction Applns
PEMFC	85-90	55/65	10 Kw stack tested. 200 kW Bus prototype	Submarine and Traction Applns
PAFC	180-200	45	Numerous static power systems	Dispersed Power systems (100kW-11MW)
MCFC	650	55	25kW stack tested 70kW, 120kW, 250kW and 1.8MW stacks test in 1993/94	Dispersed Power Applns.
SOFC	900/1000	50	25 kW stack tested 100 kW test in 1994	Dispersed Power Applns.

As indicated earlier, for practical applications cells are generally combined into stacks and stacks into larger modules. It is assumed that the minimum size of module for the applications considered here is between 5 kW (for small mobile systems) and 1 MW (for electrical power stations).

With the exception of fuel cell systems where pure hydrogen is stored, fuels generally have to be steam reformed to produce hydrogen for combination with oxygen in the fuel cell to produce electrical power, waste water and waste gases, mainly carbon dioxide, which requires disposal. The water for steam reforming could be provided from that produced by the fuel cell reaction. When steam reforming is used it is assumed that, like the fuel cell stacks, these are also modularised to provide fuel to each 5 kW to 1 MW module. This avoids problems associated with moderating the

reformer process to provide fuel for intermediate power levels or for load following.

Considering the properties in Tables 3.2 and 3.3, the types of low to medium temperature hydrogen/oxygen fuel cell that could most readily be developed at present for use in transportation applications are limited to Phosphoric Acid (PAFC), Alkaline (AFC) and Proton Exchange Membrane (PEMFC). However, of these PAFCs and AFCs have the largest weight and volume, AFCs are not tolerant to carbon dioxide and require a recirculating electrolyte system when pure gases are not used, and both AFCs and PEMFCs are not tolerant to carbon monoxide. All three of these types of fuel cell are not tolerant to the presence of sulphur in a reformed fuel. Types operating at sufficiently high temperatures to offer integrated reforming of fuels to produce hydrogen have been demonstrated in laboratories. Of these, Molten Carbonate (MCFC) types are closer to development than Solid Oxide (SOFC). MCFCs are not tolerant to the presence of sulphur in a reformed fuel whereas SOFCs are tolerant to a small amount.

In order to consider further the suitability of fuel cells for transportation applications, data on hydrogen and oxygen consumption, as well as size and weight, is required. Such data are readily available for PAFC stacks, small power AFC and PEMFC stacks, but only for laboratory and prototype MCFC and SOFC stacks. However, the data varies considerably between manufacturers, particularly for PEMFC stacks, and some is out of date.

3.5 ADVANTAGES AND DISADVANTAGES OF FUEL CELLS

The advantages of fuel cells for transportation applications have been outlined in in chapter 2, above. The marine application of fuel cells has been considered in earlier published papers (Adams, 1989, 1990) where advantages and disadvantages are given, as detailed below. These are equally applicable to all transportation applications.

The advantages of replacing IC engine driven electric power generators with fuel cell

(a) high efficiency (45% to 65% compared with 20% to 35% for IC engines) resulting in increased endurance.

(b) lower noise output (no moving parts except for pumps for fuel/oxidant or air supplies).

(c) lower running and maintenance costs with significantly increased mean time for replacement compared to diesel or gas turbine generators,

(d) savings in weight,

(e) direct generation of dc for supply to low/ medium speed electric propulsion motors,

(f) the ability to disperse fuel cell generators where required throughout the vehicle,

(g) a preliminary estimate (Adams, 1989,1990) indicates that there is no increase in through life costs when compared with diesel generators,

(h) reduced emissions from the exhaust which are harmful to the environment.

The disadvantages of replacing internal combustion engines with fuel cell systems are seen to be:

(a) new development and higher procurement costs than IC engines,

(b) the need for dc to ac conversion for auxiliaries,

(c) the need to demonstrate the ability to reform hydrocarbon or other fuels into gases suitable for use with fuel cells; this is considered chapter 5.

(d) possible difficulties in the operation of reformers and fuel cells; depending upon the design for large systems, these may both need to be modularised and one or more modules run at full power to achieve variation in the output.

The major disadvantage of high fuel cell costs compared with IC engines and the need for mass production opportunities has already been mentioned in chapter 2 and in section 3.2, above. Estimates for fuel cell units and for the percentage increase in the cost of production of fuel cell buses above their diesel equivalents vary widely; the latter from about 10% (Kevala,1990) to 23% to 33% (Hormandinger and Lucas, 1996), depending upon size.

3.6 EFFICIENCY OF FUEL CELLS

The efficiency of a fuel cell depends upon several factors in addition to the losses described at the end of section 3.3, above. Firstly, up to 15% of the fuel can be unused in a fuel cell stack and is normally recycled back through the system to help reduce this loss. Secondly, the efficiency depends upon other gases in the reactants such as from the use of air rather than pure oxygen and a fuel reformate containing carbon dioxide rather than pure hydrogen. Finally, the efficiency can vary with changes in the external load but, fuel cells have the advantage that this variation in efficiency is less noticeable than for IC engines. In later chapters (7, 8 and 9) the present analysis calculates fuel consumption and pollutants for a range of efficiency for both fuel cells and IC engines assuming that all the fuel is used, and allowance needs to be made for the above factors. This can be done by selecting results at a particular efficiency or fuel consumption, depending upon the operating conditions.

In comparing the environmental impact of fuel cells with IC engines there is a need to consider the fuel used and it's method of production. For fuel cells, whether it is pure hydrogen or a hydrogen-rich gas such as from fuel reforming, and the method of production. These aspects are considered in the next two chapters.

4. FUELS

In the future, pure hydrogen may be the fuel of choice, as Grove envisaged.
(A J Appleby, 1989, *From Sir William Grove to Today: Fuel Cells and the Future*).

4.1 INTRODUCTION

The environmental pollution of fuel cells for the transport sector are to be compared with that for internal combustion engines and re-charging batteries. In order to make this comparison more meaningful the comparison between fuel cells and engines is made for a range of fuels. These are:

(a) petroleum,
(b) diesel fuel,
(c) natural gas,
(d) propane,
(e) methanol from natural gas,
(d) methanol from processing crops,
(e) ethanol from processing crops,
(f) rape methyl ester (RME),
(g) hydrogen.

Although it is possible to use only some of these fuels in either IC engines or fuel cells at present, all are included in order to provide a comparison with potential fuels for fuel cell systems. After consideration of the various properties and methods of storage, the selection process for these fuels is given later in this chapter.

There are a number of different estimates for emissions from IC engines, for example (DeLuchi et al, 1987), (DeLuchi, 1991), (PA Consulting Group, 1992), (ETSU, 1994a), (Klaiber, 1995), (Gover et al,1996) and (IPCC, 1991 and 1995). The first three of these gives the amounts of pollutants in CO_2-Equivalents and hence cannot be

directly related to unit amounts, as already discussed in chapter 2. The remainder give estimates for various vehicles and average emissions in terms of amounts per distance travelled. The IPCC estimates are given in terms of amount per mass of fuel used as well as per distance travelled, and have been prepared for the Intergovernmental Panel on Climate Change. The amounts of CO_2 from the combustion of fuels are calculated by the author in chapter 7 and found to agree well with the IPCC estimates. Thus, the exhaust gases from the combustion of the fuels in IC engines or to provide the heat in fuel reformers are taken from the Estimation of Greenhouse Gas Emissions and Sinks prepared for the IPCC, (IPCC, 1991 and 1995). These are compared with those from fuel cells in chapter 7.

Fuels for fuel cells need to supply a source of gaseous hydrogen to the cells and can be stored as a compressed gas, a liquid or in a compound which requires some form of processing to liberate the gas. Emissions depend on the type of fuel and whether or not a process, such as steam reforming or partial oxidation followed by a shift reaction, to produce hydrogen is involved. Hydrogen as a fuel in fuel cells produces no harmful emissions, but the processing of other fuels (hydrocarbons, alcohols or RME) produces carbon dioxide or carbon monoxide, the latter needing to be removed or oxidised before the hydrogen rich gas can be used in a fuel cell. Other emissions are produced if a small amount of fuel is used to provide the heat required for the fuel reformation. The emissions from the processing of fuels are calculated by the author in chapter 7 from first principles, using the chemical equations for the steam reforming or partial oxidation of fuels. In both processes the initial reaction is followed by a steam shift reaction to convert the carbon monoxide to carbon dioxide and produce further hydrogen.

The selection of a preferred fuel depends upon safety, cost, reliability, pollution and the containment method which results in an overall weight and volume. The remainder of this chapter reviews the various possible hydrogen sources and concludes with the selection of preferred options.

It would be advantageous if any of the readily available fuels used in internal combustion engines could be used in fuel cells. However, because these fuels have a low reactivity it would be more advantageous to use fuels which are the intermediate products of the oil or chemical industries eg hydrogen, methanol, ammonia or hydrazine. Starting with hydrocarbons it is possible to produce such products by:

(a) Reforming of oil to produce CO, CO_2 and hydrogen,

(b) Separation of the products in (1) above to give hydrogen,

(c) Synthesis of the products in (1) above to give methanol and higher alcohols.

(d) Synthesis of hydrogen with nitrogen to give ammonia,

(e) Partial oxidation of ammonia to produce hydrazine.

In principle, each of these products could be used with fuel cells. Each of the fuels to be considered can be regarded as one of a number of a hydrogen fuel storage system for use with fuel cells. For the purpose of this study, four such systems have been identified, as follows:

(a) Hydrogen gas and liquid,

(b) Hydrocarbons and other chemical sources,

(c) Hydrides,

(d) Carbon based storage systems.

These are considered in the following sections 4.2 to 4.10 below, the hydrocarbons and other chemical sources being restricted to the more common fuels, as given in section

4.3. The major physical and chemical properties for each fuel considered under the above systems are given in Table 4.1. The data in this table are from various sources (Weast (1976), Boustead and Hancock (1979), RAE Cobham (1990), Gover et al (1996) and Potter, (1997).

4.2 HYDROGEN

The hydrogen/oxygen fuel cell is the simplest and as well as having the greatest number of practical solutions or possible constructions, produces the cleanest by-product, water. However, the safe storage of hydrogen for transportation applications presents some difficulties. Potential storage methods are:

(a) high pressure gas cylinders (bulky and heavy),

(b) absorption in a metal alloy known commercially as metal hydrides (bulky and heavy),

(c) cryogenic storage of liquid hydrogen, (bulky).

Hydrogen constitutes less than 1% by weight of the Earth and ranks ninth in order of abundance of elements in the planet's crust, water and atmosphere. It possesses the highest heat of combustion and the lowest density of all the fuels considered in this review. It is an odourless, colourless and tasteless gas which, as a gas, is contained in high pressure storage vessels. With present high pressure storage technology, using high strength steels, it can be stored at pressures up to 30.4 MPa. Disadvantages for transport are the weight of container vessels and hydrogen embrittlement of the steel.

TABLE 4.1 PHYSICAL AND CHEMICAL PROPERTIES OF FUELS

PROPERTIES	UNITS	FUELS:								
Name		n-Hydrogen Gas	p-Hydrogen Gas & Liq.	Methane	Methane Liquid	Propane	Propane Liquid	Petrol	Diesel	Methanol
Chemical Formula		H2	H2	CH4	CH4	C3H8	C3H8	C7H16	C16H34	CH3OH
Molecular Weight	g/mole	2.016	16.04	16.04	44.09	44.09		100.2	226.4	32.04
Density	kg/cu.m.	0.08989	71	0.7168	466	2.02	585	(684)	(840)	795
Specific Volume	cu.m/kg	11.1247	.01408	1.395	0.00215	0.495	0.00171	0.00146	0.00119	0.00126
Boiling Point	deg.C		-252.9	-164	-164	-42.1	-42.1	98.4	>200	65
Flammability in Air	vol%	4-75	4-75	5-15	5-15	2-10			1-7	6-36
Flash Point	deg.C							43	52	11
Weight % of Hydrogen	%	100	100	25.1	25.1	18.3	18.3	16.1	15.1	12.6
Vol. Density of Hydrogen	kg H2/l	0.0001	0.0710	0.0002	0.117	0.0005	0.1071	0.1101	0.1268	0.1002
Lower Heating Value	kJ/g	119.93	119.93	50.02	50.02	45.37	45.37	43.78	40.36	19.93
Higher Heating Value	kJ/g	141.86	141.86	55.55	55.55	50.41	50.41	46.08	44.4	22.69

PROPERTIES	UNITS	FUELS:		NON-RECHARGEABLE HYDRIDES:				RECHARGEABLE HYDRIDES:	
Name		Ethanol	RME	Magnesium Hydride	Calcium Hydride	Lithium Hydride	Sodium Hydride		
Chemical Formula		C2H5OH	C19H37O2	MgH2	CaH2	LiH	NaH	FeTiH2	Mg2NiH4
Molecular Weight	g/mole	46.07	297.49	26.34	42.1	7.95	24	105.7	145.7
Density	kg/cu.m.	789	880	1438	1900	820	920	5600	2730
Specific Volume	cu.m/kg	0.00127	0.00114	0.0007	0.0005	0.0012	0.0011	0.0002	0.0004
Boiling Point	deg.C	78.5							
Flammability in Air	vol%								
Flash Point	deg.C								
Weight % of Hydrogen	%	13.1	12.5	7.7	4.8	12.7	4.2	1.75	3.16
Vol. Density of Hydrogen	kg H2/l	0.1034	0.11	0.111	0.0912	0.1041	0.0387	0.098	0.0863
Lower Heating Value	kJ/g	26.71	29.68						
Higher Heating Value	kJ/g	33.9	37.1						

Development work is proceeding on lightweight composite cylinders of Kevlar and graphite wound on aluminium shells in order to increase the gravimetric energy density. Disadvantages of using hydrogen gas stored systems are:

(a) poor volumetric and gravimetric energy densities for gas plus containment.

(b) potential explosion hazard under certain accident scenarios where failure of containment vessels occurs.

(c) causes permanent embrittlement in steel.

(d) highly inflammable over a broad range of mixtures with air.

Hydrogen could be liquefied for storage on vehicles where it could be gasified, using waste heat once a system is operational. It is a gas at normal atmospheric conditions and a mixture of two isometric forms, called para-hydrogen and ortho-hydrogen, distinguished by their nuclear spins. During a commercial liquefaction process the predominant ortho form is converted to para-hydrogen. Being a naturally slow process, it is normally assisted with catalysts to achieve the highest content of para-hydrogen. This is necessary in order to minimise boil-off losses which has a direct relationship with the concentration of ortho-hydrogen in the storage vessel. Cryogenic storage vessels for minimising heat transfer are normally multi-shell designs with a vacuum interstitial space and multi-layer aluminised Mylar insulation. Small Dewar flasks of 140 litre capacity designed for transport applications have boil-off losses of about 1.8% per day (Ballard Power Systems, 1992). Larger systems with lower surface area to volume ratios can have losses of less than 1% per day. Venting of this boil-off gas is necessary to avoid excessively high internal pressures, and since hydrogen is required and fuel in gaseous form, vaporisation of the liquid is required. Advantages are:

(a) fuel requires minimal processing for use.

(b) mature storage technology with optimisation to minimise boil-off losses.

Disadvantages of liquid hydrogen are:

(a) poor liquid plus containment volumetric energy density for gas plus containment.

(b) requires complex cryogenic storage system.

(c) energy intensive processing to produce para-hydrogen liquid.

(d) boil-off must be relieved through venting or consumption.

(e) safety concerns similar to gaseous hydrogen.

(f) causes permanent embrittlement in steel.

(g) poor availability compared with other fuels.

(h) highly flammable over a broad range of mixtures with air.

4.3 HYDROCARBONS AND CHEMICAL FUELS

Hydrocarbons can be reformed or broken down into mainly hydrogen and carbon dioxide to produce a hydrogen rich gas suitable for use in most types of fuel cell. The reforming process requires a heat input and the amount of hydrogen obtained is dependent upon the fuel used. They have the advantage of storage at normal temperature and normal or moderate pressure. Different fuels require different heat inputs to break down the molecules, and the reforming temperature varies from $250^{O}C$ to $650^{O}C$.

Other problems associated with hydrocarbon fuels are the presence of sulphur and the possible, but unlikely, presence of additives in readily available products that could poison the catalysts used in the reformer. Desulphurization is necessary to avoid poisoning the fuel cell catalyst and this possibly could be achieved after the reforming reaction by hydrogenating the sulphur compounds using some of the product hydrogen, thus removing the sulphur as hydrogen sulphide. The only potential candidate for the direct (internally to the fuel cell system) reforming of a hydrocarbon without desulphurization is the solid oxide type of fuel cell, although SOFC's are not as sulphur tolerant as internal combustion engines.

Apart from the solid oxide type, fuel cells are intolerant to sulphur. It is claimed by Westinghouse (Appleby and Foulkes, 1989, p584) that the solid oxide fuel cell anode (fuel electrode) can be made with a high tolerance to sulphur; the presence of 50 ppm by volume of hydrogen sulphide in the fuel lowers the operating voltage by only about 5%, causing no damage to the cell. At $1000^{o}C$, nickel or cobalt cermet anodes have been assigned (Fee and Ackerman, 1983) sulphur tolerances of 90 and 200 ppm by volume or about 0.021% and 0.047% by mass, respectively. These tolerances are between one and two orders of magnitude lower than the worst accepted sulphur levels in hydrocarbon fuels. They are, however, one or two orders of magnitude higher than sulphur tolerances for other types of fuel cell, and permit the use of high-temperature methods of sulphur removal, which are more efficient than, for example, the low-temperature methods required by molten carbonate fuel cells to lower the sulphur content in this case to less than 1 ppm by volume (Appleby and Foulkes, 1989, p585). Unless legislation causes a change to use low levels of sulphur in fuel, the above tolerances require a sulphur removal system to be integrated with the fuel reformer.

The following common alcohol and hydrocarbon fuels are examined as sources of a hydrogen rich gas:

(a) methyl alcohol or methanol

(b) ethyl alcohol or ethanol

(c) rape methyl ester (RME)

(d) kerosene and petroleum

(e) diesel fuel

(f) methane gas

(g) natural gas, which for North Sea gas is over 93% methane

(h) propane gas

(i) liquid propane gas.

4.4 ALCOHOLS

4.4.1 METHANOL

Methanol is an interesting compromise between hydrogen and hydrocarbons because of its reactivity, and it is possible to make fuel cells which use it directly. Higher alcohols (ethanol, propanol, glycerol, etc) could be used as fuel but complete oxidation to carbon dioxide is slower than with methanol. It can be stored easily as a liquid and could be made available at pumps in a similar fashion to petrol. However, attempts to develop direct methanol fuel cells have met with difficulties and the most promising method is to employ a reformer to produce hydrogen for a hydrogen/oxygen fuel cell.

A liquid under normal conditions, methanol is manufactured in large quantities from natural gas and coal and storage is possible in metal tanks. More than 80% of

methanol is currently produced from natural gas (Johansson et al, 1993, p893), by steam reforming (see below and chapter 5) natural gas to produce a mixture of mainly carbon dioxide and hydrogen. Methanol is then produced by combining the carbon dioxide and hydrogen in a synthesiser to first produce carbon monoxide and hydrogen, followed by the synthesis of these last two gases into methanol. The merits of producing methanol as a liquid fuel by the above processes involving methane need to be considered against those of using natural gas or methane directly as a gaseous fuel.

Alternatively, biomethanol can be produced by processing wood to methane, followed by a process similar to that for chemical grade methanol, above, to produce crude methanol which is then distilled to produce the required purity (Gover et al, 1996, Vol 2, p124). However, since the energy yield in the UK is 120 GJ/hectare of land (ETSU, 1994a, Vol 7), or about 600 kg of methanol/hectare, large areas of land need to be set aside to provide sufficient fuel for the UK vehicle market alone. Also, other industrial crops and energy sources such as wind turbines could be expected to compete for the set aside land. Thus, biomethanol could only be expected to provide fuel for niche markets such as particular delivery vehicles or urban transport.

Although the energy density of methanol in terms of volume is superior to liquid hydrogen, it has to be steam reformed to produce a hydrogen rich gas for use in a fuel cell. Direct methanol fuel cells are being studied, but are currently at the laboratory stage. In steam reforming, water is added to methanol and the solution is vaporised and passed over a catalyst to produce hydrogen and carbon monoxide. A secondary water shift reaction produces further hydrogen from the carbon monoxide and steam. The resultant gas is a hydrogen rich mixture of hydrogen (75%) and carbon dioxide. Any residual carbon monoxide must be removed before the gas can be used in some types of fuel cell (alkaline and PEM).

The advantages of methanol are:

(a) good volumetric and gravimetric energy densities for liquid plus

containment.

(b) liquid under ambient conditions.

(c) simple, non pressurised storage tanks.

(d) established production capabilities used world-wide (20 million tonnes per year).

(e) reforming process well known and small systems suitable for transport are under development.

The disadvantages of methanol are:

(a) energy required for processing reforming.

(b) residual carbon monoxide in reformate gas must be eliminated for some types of fuel cell (alkaline and PEM).

(c) reformer exhaust product of carbon dioxide.

4.4.2 ETHANOL

Ethanol can be produced from natural gas or crude oil but is now widely available in Brazil, where it is made from sugarcane, and to a lesser degree in the USA, where it is made from maize (corn), (Johansson, et al, 1993, p35). Producing ethanol from sugar crops involves milling, boiling, fermentation and distillation (ibid, p850). The production of ethanol from starch crops such as corn involves milling, mixing with hot water and adding an enzyme to produce sugar in a "cooking" process, fermentation and distillation (Gover et al, 1996, p139). However, the same argument applying to biomethanol for yield/hectare of land applies so that it could only supply fuel for niche markets. For use in a fuel cell ethanol needs to be reformed but the temperature of

reformation is higher than that for methanol. Advantages and disadvantages are similar to those for methanol.

4.5 RAPE METHYL ESTER (RME) OR BIODIESEL

Methyl esters can be produced from a range of vegetable oils including rapeseed oil, palm oil, sunflower oil and soyabean oil (Gover et al, 1996, p151). They are produced by the reaction between organic acids and alcohol, methyl esters being formed by using methyl alcohol or methanol. Thus, esters may be regarded as organic salts of acids, and an ester is produced for instance, when the hydrogen of the carboxyl group of an organic acid is replaced by an organic radical (R) containing a -COOR grouping.

Rapeseed oil, one of the main oilseed crops grown in Europe, is reacted with methanol to produce rape methyl ester (RME) and glycerine ($CH_2OH.CHOH.CH_2OH$) which are then separated. This reaction is carried out at or near room temperature in the presence of a catalyst (Gover et al, 1996, p157). The oil consists of a triglyceride molecule:

$$CH_2.O.CO.R1\text{-}CH.O.CO.R2\text{-}CH_2.O.CO.R3$$

which has a range of fatty acids (R1, R2 and R3) attached to it, mainly (about 65%) oleic acid (Potter, 1997). Taking oleic acid ($C_{17}H_{35}.COOH$) as the main constituent, the reaction with methanol is:

$$C_6H_5O_6.3C_{17}H_{35}.COOH + 3CH3OH \longrightarrow$$
$$CH_2OH.CHOH.CH_2OH + 3C_{17}H_{35}\ COOCH_3$$

Once the RME has been separated from the glycerine it can be used in internal combustion engines; it is assumed in the next chapter that it can be steam reformed and partially oxidised in the same way as alcohols and hydrocarbons.

However, since the yield in the UK is 1.18 tonnes/hectare of land (ETSU, 1994a, Vol

7), large areas of land would need to set aside to provide the potential UK requirement alone, amounting to over 18 million tonnes/year of diesel and derv.

4.6 HYDROCARBONS

With current technology, hydrocarbon fuels have to be processed to produce hydrogen for use with fuel cells. The use of reformed hydrocarbons with fuel cell systems would reduce the harmful emissions in the waste gases compared with conventional power generation and transportation systems. Reforming temperature and pressures are generally higher than that for alcohols, but desulphurization of the fuels prior to reformation using a catalyst, must be included. Exhaust gases would consist typically of carbon dioxide from the fuel and unused gases (other than oxygen) from the input air, with minimal amounts of carbon monoxide, sulphur and nitrogen compounds and unused hydrocarbons. Other emissions would be produced if a small amount of fuel is used to provide the heat of reformation.

Crude oils, consisting primarily of hydrocarbons and compounds containing sulphur, are the source of currently the most abundant fuels which are made by fractional distillation.

4.6.1 KEROSENE AND PETROLEUM

Kerosene is a common commercial fuel used in a large range of applications from oil lamps to aircraft fuel. Petroleum is used mainly in internal combustion engines for light to medium road transport. It consists mainly of heptane with other higher hydrocarbons up to decane. Both petroleum and kerosene are liquid at ambient conditions allowing storage in conventional metal containers. Kerosene is less volatile than petroleum and has a higher flash point. Their volumetric energy densities are higher than both liquid hydrogen and methanol.

The advantages of kerosene and petroleum are:

(a) good volumetric and gravimetric energy densities for liquid plus containment.

(b) common distillates of crude oil.

The disadvantages of kerosene and petroleum are:

(a) require desulphurization.

(b) require high temperatures and pressures for reforming process.

(c) reformer exhaust product of carbon dioxide.

(d) desulphurization produces sulphide (typically zinc sulphide).

4.6.2 DIESEL FUEL

Diesel fuel, consists of about 66% hexadecane with xylene, napthalene and sulphur compounds. It is distilled from crude oil, is liquid at ambient temperatures and has a high volumetric energy density compared with liquid hydrogen. It has high levels of sulphur which must be removed prior to the reforming process, which takes place at a higher temperature and pressure than kerosene.

The advantages of diesel fuel are:

(a) good volume and gravimetric energy densities for liquid plus containment.

(b) common fuel worldwide.

The disadvantages of diesel fuel are:

(a) requires desulphurization.

(b) requires very high temperature and pressure for reforming process.

(c) reformer exhaust product of carbon dioxide.

(d) desulphurization produces sulphide (typically zinc sulphide.

4.6.3 METHANE GAS

Methane gas has a high energy density but the weight of high pressure cylinders used for storage tend to decrease the overall gravimetric energy density of a system. However, the development of high pressure vessels as for hydrogen above, could reduce this problem. The advantage of methane gas is that it is a readily available fuel derived from natural gas.

The disadvantages of methane gas are:

(a) relatively poor volume and gravimetric energy densities for gas plus containment.

(b) high storage system weight.

(c) high reforming temperature and pressure.

(d) reformer exhaust of carbon dioxide.

4.6.4 NATURAL GAS

Natural gas is an abundant fuel world-wide consisting of approximately 87% methane with ethane, propane and butane. Storage is in high pressure vessels but development

as for hydrogen gas storage above, could increase the overall gravimetric energy density of a system.

The disadvantages of natural gas are:

(a) relatively poor overall volume and gravimetric energy densities for gas plus containment.

(b) high storage pressure weight.

(c) high reforming temperature and pressure.

(d) reformer exhaust of carbon dioxide.

4.6.5 LIQUEFIED NATURAL GAS (LNG)

Natural gas and methane liquefy at -161^{O}C and have a higher volumetric and gravimetric energy densities than liquid hydrogen.

The advantages of LNG are:

(a) good volumetric and gravimetric energy densities for liquid plus containment.

(b) conventional cryogenic storage.

The disadvantages of LNG are:

(a) boil-off gas needs to be vented or consumed.

(b) high reforming temperature and pressure.

(c) reformer exhaust of carbon dioxide.

4.6.6 PROPANE

Propane is the main constituent of Liquefied Petroleum Gas (LPG) which consists of approximately 90% propane with butane, propylene and butylene.

4.7 AMMONIA

In the gaseous form ammonia has poor volumetric and gravimetric energy densities for gas plus containment but, in the liquid form these are comparable with methanol and LNG. A hydrogen rich gas (75% hydrogen and 25% nitrogen) is produced by dissociation at 700^{O}C over a catalyst.

The advantages of ammonia are:

(a) dissociation produces no fuel cell catalyst poisons.

(b) good volumetric and gravimetric energy densities in the liquid form for liquid plus containment.

The disadvantages of ammonia are:

(a) requires high temperature to dissociate into hydrogen mixture.

(b) toxic.

(c) problems with distribution and safe storage on transport vehicles.

4.8 HYDRAZINE

Compared with other liquid fuels for direct feed to fuel cells, hydrazine gives the best results. It could also be decomposed to produce hydrogen for use in fuel cells but, although it is easy to transport and store in solution, depending upon purity, it is explosive. It is also highly toxic and for this reason hydrazine fuelled cells are unlikely to be developed.

4.9 HYDRIDES

Two types of hydride are considered. The first are rechargeable hydrides where a metal alloy reacts reversibly with hydrogen at various temperatures and pressures:

(a) iron titanium hydride ($FeTiH_{1.95}$).

(b) magnesium nickel hydride (Mg_2NiH_4.

The second are chemical hydrides formed with metals which release hydrogen and heat when reacted with water:

(a) magnesium hydride (MgH_2).

(b) calcium hydride (CaH_2).

(c) lithium hydride (LiH).

(d) sodium hydride (NaH).

(e) lithium aluminium hydride ($LiAlH_4$).

(f) lithium borohydride ($LiBH_4$.

4.9.1 RECHARGEABLE HYDRIDES

These alloys react reversibly with hydrogen and over a range of temperature and pressure. During charging heat is generated and must be removed as the charge of hydrogen increases. The purity of the source hydrogen must be high, with no water vapour. Regeneration of the hydrogen is achieved by the addition of heat.

Iron titanium hydride is commonly used and has a hydrogen capacity of about 1.75% by weight.

The advantages of iron titanium hydride are:

(a) low heat of operation.

(b) ambient temperature operation.

(c) higher volumetric energy density than liquid hydrogen for gas plus hydride and containment.

(d) low cost.

The disadvantages of iron titanium hydride are;

(a) poor gravimetric energy density for gas plus hydride and containment.

(b) hydrogen source gas must be of high purity.

(c) hydride poisoned by carbon monoxide, water or oxygen.

Magnesium nickel hydride has a higher capacity than other hydrides at over 7% by weight but, also has a higher heat of dissociation.

The advantages of magnesium nickel hydride are:

(a) higher hydrogen storage capacity than iron titanium hydride.

(b) higher volumetric energy density than liquid hydrogen for gas plus hydride and containment.

The disadvantages of magnesium nickel hydride are:

(a) high heat and temperature of dissociation.

(b) poor gravimetric energy density for gas plus hydride and containment.

(c) hydrogen source gas must be of high purity.

(d) hydride poisoned by carbon monoxide, water or oxygen.

4.9.2 NON-RECHARGEABLE HYDRIDES

These hydrides react irreversibly with water to form hydrogen and precipitate a solid product. They have good volumetric and gravimetric energy densities but some react violently with water.

The disadvantages of non-rechargeable hydrides are:

(a) high costs and poor availability.

(b) highly reactive to moisture with potential for violent reaction.

(c) highly exothermic reaction.

(d) precipitate of reaction can be up to three times the volume of hydride and can be difficult to remove.

4.10 CARBON BASED STORAGE SYSTEMS

Two carbon based technologies for hydrogen storage are under consideration by the transport industry in the USA. The first involves superactivated charcoal at about -123^{O}C and at least 55 atmospheres pressure, which then absorbs hydrogen. To date, a 5% hydrogen storage by weight has been demonstrated where absorption occurs at 80 atmospheres and subsequent storage is at 55 atmospheres. Hydrogen is released by reducing the pressure and increasing the temperature. The second technology involve graphitic alkali intercalates. Hydrogen is absorbed by alkali metals, such as sodium and potassium, which are intercalated with a graphite such as boron carbide.

The advantage of carbon based storage systems for hydrogen is the low material cost.

The disadvantages are:

(a) need to maintain low temperature.

(b) early state of development.

4.11 SELECTION OF FUEL FOR FUEL CELLS

4.11.1 FUELS WHICH REQUIRE PROCESSING

A number of the above fuels have significant disadvantages in processing to produce a

hydrogen rich mixture suitable for use with fuel cells. These are kerosene, petroleum, ammonia, non-rechargeable and hydrides. Others, namely diesel fuel, propane, methane, methanol and ethanol are considered to be more suitable candidates. Each of the above fuel are discussed briefly below.

Kerosene and petroleum require high temperature and pressure reformers but are retained as fuels for further consideration since suitable reforming or other breakdown processes, such as partial oxidation, may be developed. Even if such processes do not lend themselves to systems on-board vehicles, they might in future prove suitable for central reforming plants from where hydrogen could be distributed. Also, petroleum is considered for the comparison with IC engines because it is currently one of the main transport fuels.

Ammonia requires development for processing as a fuel and is toxic, especially in confined spaces, and will not be considered further.

Non-rechargeable hydrides need to be stored and processed as solids in relatively large quantities. Other concerns are their explosive nature on contact with water and high cost, and consequently they will not be considered further.

Diesel fuel has been retained because reformers and other breakdown processes, such as partial oxidation, suitable for transport systems are under consideration or development. Also, future development of high temperature fuel cells, such as the solid oxide type, might make diesel a suitable fuel for internal or integrated reforming. As for petroleum, diesel fuel is considered for the comparison with IC engines because it is one of the current main transport fuels.

Methanol, ethanol, methane and natural gas have lower reforming temperature and pressure requirements than petroleum or diesel fuel and are considered to be suitable candidates for further consideration. Also, they would be suitable for internal reforming with future developed high temperature fuel cells or with other breakdown

processes, such as partial oxidation. These fuels also are suitable candidates for comparison with IC engines because they are currently being considered as alternative fuels for conventional road vehicles.

Propane also has been retained for comparison because systems are being developed for conventional engine driven vehicles. Also, it could be used with future developed high temperature fuel cells or with a system using partial oxidation.

The processing of fuels for fuel cell systems is considered in the next chapter.

4.11.2 HYDROGEN

Hydrogen has disadvantages since it must be stored in relatively heavy containers as a high pressure gas, cryogenic liquid or in a heavy rechargeable hydride. Also, it's high flammability over a broad range of mixtures with air has made hydrogen unpopular as a transport fuel.

Alloy based rechargeable metal hydride storage systems have high densities and low hydrogen storage capacity resulting in a low gravimetric energy density. This type of storage system is considered to be the safest when compared with other systems for either gaseous or liquid hydrogen. However, the low energy density probably makes them unsuitable for most transport systems except in some special circumstances. A highly successful submarine fuel cell system using metal hydride hydrogen and liquid oxygen storage has been demonstrated by Germany (Knaak, 1986) and (Foxwell, 1988). The system used alkaline fuel cells manufactured by Siemens (Strasser, 1989) but for future development the use of proton exchange membrane fuel cells was proposed.

Carbon based hydrogen storage systems may be developed in future but their volumetric and gravimetric energy densities could be unacceptably low. These low densities coupled with the relatively complicated processes required to release the

hydrogen are significant disadvantages in their use with fuel cells.

However, hydrogen is retained because safe storage methods and safety precautions suitable for transport systems are under development. Also, it has the following distinct advantages, possibly making it the preferred fuel of the future:

(a) the highest heat of combustion,

(b) the lowest density,

(c) the cleanest fuel with zero harmful emissions.

(d) production by electrolysis of brine from seawater using renewable sources of energy.

4.12 SUMMARY

This chapter has considered a range of potential fuels for providing hydrogen for use with fuel cells; some have been rejected and others retained for further consideration in later chapters. The next chapter considers the processing of hydrocarbons, alcohols and rape methyl ester into a mixture of hydrogen and carbon dioxide for use as a fuel in fuel cells.

5. FUEL PROCESSING

There has been a revolutionary trend away from processes based on solid fuel toward those based on the use of hydrocarbon gas and oil reforming.
(British Petroleum Co, 1972, *Gasmaking).*

5.1 INTRODUCTION

This chapter considers the processing of fuels, such as hydrocarbons and alcohols, to produce hydrogen for use in fuel cells, and has drawn on published data (BP, 1972), (Appleby and Foulkes, 1989) and (Dicks, 1995) for background information. Most types of fuel cell will tolerate a mixture of hydrogen and carbon dioxide as a fuel but are intolerant to carbon monoxide and sulphur. Also, most catalysts suitable for fuel processing are intolerant to sulphur. Thus, the fuel processing must include desulphurization before fuel processing and the removal of carbon monoxide from the product gas after fuel processing.

Currently, the only practical fuel for use in fuel cells is hydrogen and the reaction mechanisms are well understood, resulting in pure water being produced. On the other hand, other fuels such as hydrocarbons or alcohols have slow hydrogen producing reaction rates at temperatures below about $300^{O}C$ and their breakdown results in other products, which can be poisonous to catalysts. At temperatures above about $900^{O}C$ and in an inert atmosphere, hydrocarbons tend to decompose to hydrogen and carbon, the latter giving problems of deposition and disposal. This decomposition can be can be prevented by adding steam to the fuel resulting in the formation of hydrogen, carbon monoxide and carbon dioxide. The carbon monoxide can be removed by the addition of further steam, producing hydrogen and carbon dioxide, resulting in hydrogen as the fuel.

Thus, when fuels are processed to produce hydrogen, temperatures in excess of $300^{O}C$ are used. Also, water must be used in the process, generally known as steam

reforming, where the oxygen from the water appears as carbon monoxide and carbon dioxide. This results in the energy density of the product being less than that of the original fuel, except when the water can be provided by condensation of the water produced by the fuel cell itself.

5.2 DESULPHURIZATION

Almost all sulphur in liquid hydrocarbon fuels is present in the form of thiols (based on C_4H_8S), sulphides or disulphides and thiophenes (based on C_4H_4S). Thiols and disulphides are generally less stable and easier to remove and hence the effectiveness of a desulphurization catalyst is usually judged by its ability to remove the organic sulphides and thiophenes. The catalytic decomposition of organic sulphur compounds results in the formation of hydrogen sulphide and unsaturated hydrocarbons. However, the thermodynamic equilibrium is usually unfavourable for such reactions below $400^{O}C$ and higher temperatures can be detrimental to catalyst life.

In practice, hydrodesulphurization is usually preferred where catalytic decomposition occurs in the presence of hydrogen at temperatures between $300^{O}C$ and $400^{O}C$, resulting in the formation of hydrogen sulphide and saturated hydrocarbons with more favourable thermodynamic equilibrium. Often the presence of steam is required to suppress carbon formation and fouling of the catalyst bed. Typical hydrodesulphurization catalysts are a sulphided form of zinc, iron, cobalt, nickel, chromium, molybdenum or tungsten. Retention of the hydrogen sulphide is needed and can be achieved by:

(a) a two step process in which a catalyst is either mixed with an absorbing material or followed by a separate absorption step (zinc oxide or iron oxide is usually the absorbing material in both cases).

(b) a one-step process using a material (eg nickel) absorbing the hydrogen sulphide (this usually requires the presence of water and is only suitable for

steam reforming processes).

The hydrogen for the hydrodesulpurization process can be obtained by recycling some of that produced by a fuel reformer (Ohnishi,1995) and (Ikeda, 1995).

Sulphur removal at high temperature is preferable (Appleby and Foulkes, 1989) because of thermodynamic efficiency and ease of integration into a high temperature fuel cell system, such as one using a solid oxide fuel cell. The use of iron oxide-silica absorbents at about 650^{o}C has been used to remove sulphur levels from about 6000 ppm by volume to about 200 ppm in coal synthesis gas (Jalan, 1981).

Low temperature desulphurization reported by Osaka Gas in Japan (Okada et al, 1992), using a mixed metal and metal oxide catalyst, claims to remove organic sulphur and hydrogen sulphide at room temperature, thus reducing start up time for fuel cell power generator. A combination of this method with conventional hydrodesulpurization is claimed to result in a fuel gas with less than 0.1 ppb sulphur.

Other low temperature sulphur adsorption using activated carbon or molecular sieves do not need hydrogen, but are impracticable for large systems because of the amount of absorbent required, problems with reactivation and disposal of the desorbed sulphur. Activated carbon is chemically impregnated to enhance hydrogen sulphide adsorption, but is only suitable for small systems for relatively short periods.

5.3 HYDROCARBONS

5.3.1 STEAM REFORMING

In principle, hydrocarbons can be steam reformed to produce a mixture of hydrogen and carbon monoxide, followed by a water shift reaction with further steam, which converts the carbon monoxide to more hydrogen and carbon dioxide:

$$C_nH_{(2n+2)} + nH_2O \longrightarrow (2n+1)H_2 + nCO \quad [1]$$

$$CO + H_2O \longrightarrow H_2 + CO_2 \quad [2]$$

It is possible for these two reactions to take place in the same reactor. For an unsaturated hydrocarbon the first reaction becomes:

$$C_nH_{2n} + +nH_2O \longrightarrow 2nH_2 + nCO \quad [3],$$

and the overall reactions are:

$$C_nH_{(2n+2)} + 2nH_2O \longrightarrow (2n+1)H_2 + nCO_2 \quad [4]$$

$$C_nH_{2n} + 2nH_2O \longrightarrow 3nH_2 + nCO_2 \quad [5]$$

These reactions are endothermic and normally carried out over a nickel catalyst on a refractory support at temperatures above about 500^{o}C. The reactions are reversible and very fast. In order to avoid any carbon deposition:

$$2CO = CO_2 + C \quad [6],$$

the quantity of steam added is well in excess of the stoichiometric value for equation [1] so that the equilibrium of equation [1] moves towards more CO_2 rather than CO. Given the equilibrium constants for the above reactions, the atomic ratios and the operating temperature and pressure, it is possible to estimate the composition of the output reformate gas.

5.3.2 OTHER METHODS

Other methods of hydrocarbon conversion (partial oxidation, thermal cracking and

chemical reduction) have the disadvantage of producing hydrogen and carbon monoxide rather than carbon dioxide.

Partial oxidation:

$$2C_nH_{(2n+2)} + nO_2 \longrightarrow 2nCO + (2n+2)H_2 \quad [7],$$

produces less hydrogen per mole than the first reaction of steam reforming, equation [1] above. The carbon monoxide can be shifted to carbon dioxide and hydrogen by the addition of steam, equation [2] above, but the amount of hydrogen produced from both reactions, equation [8] below, will be less than that from steam reforming by the ratio $(2n+1)/3n+1)$ for a saturated hydrocarbon, C_nH_{2n+2}. Also, since the partial oxidation reaction is exothermic it cannot make use of any waste heat, such as from a high temperature fuel cell. Even though the process is less complex than steam reforming it requires several subsystems; heat exchangers to heat the air before fuel is added; a reaction chamber. Both systems require a cleanup system to remove sulphur and any other contaminants which can affect fuel cell catalysts.

Partial oxidation, followed by a steam shift reaction to convert the carbon monoxide to carbon dioxide and further hydrogen, could be used for the conversion of a number of hydrocarbon fuels to hydrogen and carbon dioxide mixture, with an overall reaction:

$$2C_nH_{(2n+2)} + nO_2 + 2nH_2O \longrightarrow (4n+2)H_2 + 2nCO_2 \quad [8].$$

Thermal cracking, by heating without air, produces hydrogen and carbon and has the disadvantage of disposal of the solid carbon:

$$C_nH_{(2n+2)} \longrightarrow nC + (n+1)H_2 \quad [9].$$

This method is that involved directly in high temperature fuel cells and, where the steam/carbon ratio is low, leads to problems of deposition on the fuel cell catalyst.

Some refractory metal oxides can be reduced at temperature above 900^{o}C in a gas such as methane to produce the metal, carbon monoxide and hydrogen. The metal can then be oxidised in air or oxygen for further reduction with more methane, but the activity decreases with repeated oxidation and reduction cycles.

5.4 ALCOHOLS

Steam reforming can be applied to alcohols such as methanol or ethanol, and methanol has been considered for mobile fuel cell systems eg (Adams, 1989 and 1990), (Lemons, 1989) and (Hohlein et al, 1995):

$$CH_3OH + H_2O \longrightarrow CO + 3H_2O \quad [10]$$

followed by a similar shift reaction to equation [2]:

$$CO + H_2O \longrightarrow CO_2 + H_2 \quad [11]$$

giving an overall reaction of:

$$CH_3OH + H_2O \longrightarrow CO_2 + 3H_2 \quad [12].$$

Reforming of ethanol takes place at a higher temperature:

$$C_2H_5OH + H_2O \longrightarrow 2CO + 4H_2 \quad [13]$$

followed by a shift reaction:

$$CO + H_2O \longrightarrow CO_2 + H_2 \quad [14]$$

giving an overall reaction:

$$C_2H_5OH + 3H_2O \longrightarrow 2CO_2 + 6H_2 \quad [15]$$

5.5 METHYL ESTERS

These fuels can be used in internal combustion engines, and it is assumed that they can be steam reformed and partially oxidised in the same way as alcohols and hydrocarbons. The ester considered in this thesis is rapeseed methyl ester (RME) with a chemical formula assumed to be $C_{19}H_{38}O_2$, see chapter 4.

Steam reforming of RME is assumed to take place in two stages as follows:

$$C_{19}H_{38}O_2 + 17H_2O \longrightarrow 36H_2 + 19CO \quad [16]$$

followed by a shift reaction:

$$CO + H_2O \longrightarrow H_2 + CO_2 \quad [17]$$

giving an overall reaction:

$$C_{19}H_{38}O_2 + 36H_2O \longrightarrow 55H_2 + 19CO_2 \quad [18]$$

Partial oxidation of RME, followed by a steam shift reaction above, is assumed possible. Partial oxidation:

$$2C_{19}H_{38}O_2 + 17O_2 \longrightarrow 38H_2 + 38CO \quad [19]$$

followed by equation [17] above, gives an overall reaction:

$$2C_{19}H_{38}O_2 + 17O_2 + 38H_2O \text{ ----> } 76H_2 + 38CO_2 \quad [20]$$

5.6 EXTERNAL STEAM AND PARTIAL OXIDATION REFORMING

External reformers are defined as those which operate separately from a fuel cell or other power source. The technology of steam reformers has been well documented, eg (BP, 1972) , (Rostrup-Nielson et al, 1984), Ridler et al, 1989) and (Dicks, 1995) and there are several different types, particularly for natural gas as described in the paragraphs below. The descriptions of the various types of reformer below, have been adapted from (Dicks, 1995).

Regenerative cylindrical reformers, designed for fuel cell power generation systems, are compact, have a high thermal efficiency and usually burn some fuel to provide the heat of reformation. They can have a multi tube assembly inside a burner vessel as shown in Figure 5.1 (Krar et al, 1978) and (Cohen et al, 1989), or a central burner as shown in Figure 5.2 (Undengaard et al, 1987)

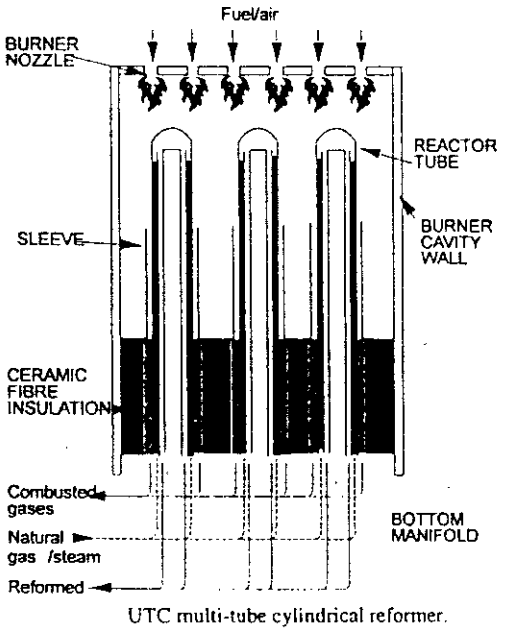


Figure 5.1 (Cohen et al, 1989)

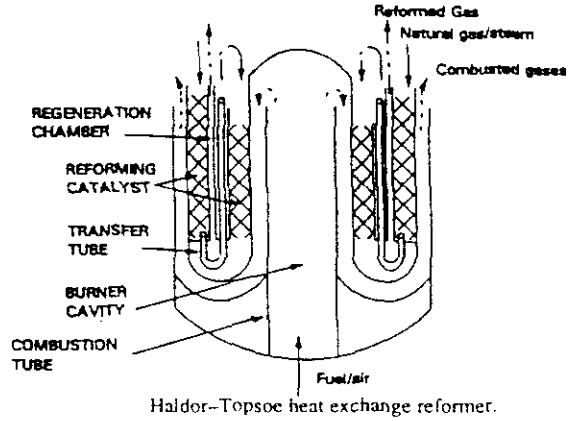


Figure 5.2 (Undengaard et al, 1987)

Plate reformers, in which plates separate a stack of alternate combustion and reforming vessels as shown in figure 5.3 (Wananabe et el, 1988). Other plate reformers are reported in the literature (Ohnishi, 1995) and (Minet and Warren, 1897).

Spiral or Annular reformer, in which the reforming chamber is an annular space with spiral shaped catalyst passageways, and the incoming gas is heated in chamber by the reformed gas. Heat for the reaction is provided by gas combustion in a hollow outer wall as shown in Figure 5.4 (Astanovsky et al, 1992).

Reformers have been proposed with palladium molecular sieves or membranes (Kikuchi et al, 1991) which selectively removes the hydrogen from the reforming reaction, increasing the reaction conversion level and producing very pure hydrogen. However, palladium is relatively expensive and experiments are underway using ceramic membranes (ETSU, 1994b).

A simplified reformer which combines desulphurization, steam reforming and the shift reaction in a single vessel where inert packing material, desulphuring zinc oxide,

reforming catalysts, more inert packing material and finally a shift catalyst are arranged in layers. Heat for the reaction is provided by the packing and catalyst materials, where the packing is heated first by steam and then by combusted gases in cycles (Wertheim and Sederquist, (1989).

Proposals have also been made for steam reforming in an electric arc plasma (Bromberg et al, (1995), where the plasma is controlled by a magnetic field in a cylindrical vessel providing compactness, fast start up and quick response to load change, as shown in Figure 5.5. Magnetic control of electric arc plasmas have been extensively studied in the past and used for control of gases in hypersonic wind tunnels and circuit breakers (Adams, 1968).

Partial oxidation reformers operating at temperatures of about $1200^{O}C$ to $1400^{O}C$ provide steam reforming with little or no steam and without a catalyst, (Calcott and Deague, 1977) and (Pietrogrande et al, 1993). A mixture of fuel and air is oxidised to produce carbon dioxide and steam which then react with a second fuel stream, downstream of the combustion area, to produce a hydrogen/carbon monoxide mixture.

Catalytic partial oxidation reformers operate at about $500^{O}C$ and require less preheating of the feed gas. A *Hot Spot* reactor (Jenkins, 1990) uses a partial oxidation catalyst packed in a single vessel which produces a hot spot in the centre of the catalyst bed; this hot spot is caused by injection of the fuel/air mixture at that point, as shown in Figure 5.6. If steam is added to the fuel mixture the heat generated by the exothermic partial oxidation reaction may be balanced by endothermic steam reforming reaction. Such reactors are generally called *Autothermal* and have the advantage for fuel cell applications in that they do not require an external heat source, have a fast startup time and can start without steam; steam can be then generated using waste heat from the fuel cell system. There are several published examples, (Marsh and Thiagarajan, 1992), (Dunster and Korchnak, 1989), Nielson-Rostrop et al, 1992) and Hwang, et al, 1985). The last, shown in Figure 5.7, has been developed for fuel cells and is successful with higher hydrocarbons, such as diesel oil, without any carbon deposition.

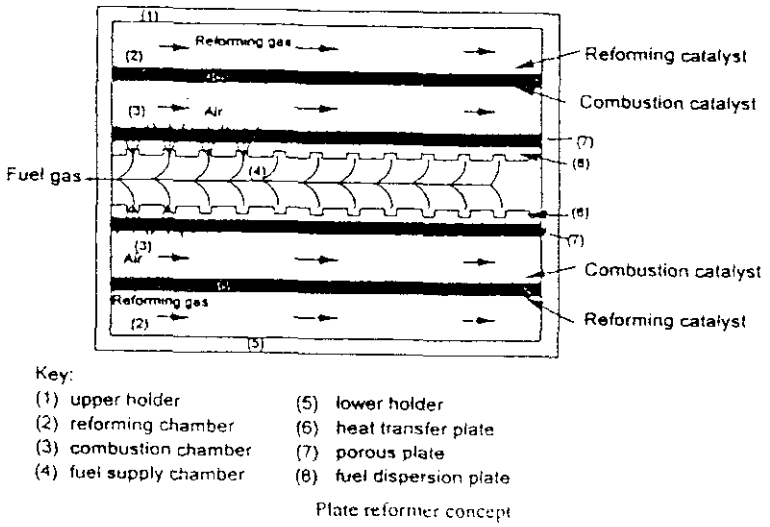


Figure 5.3 (Wananabe et al, 1988)

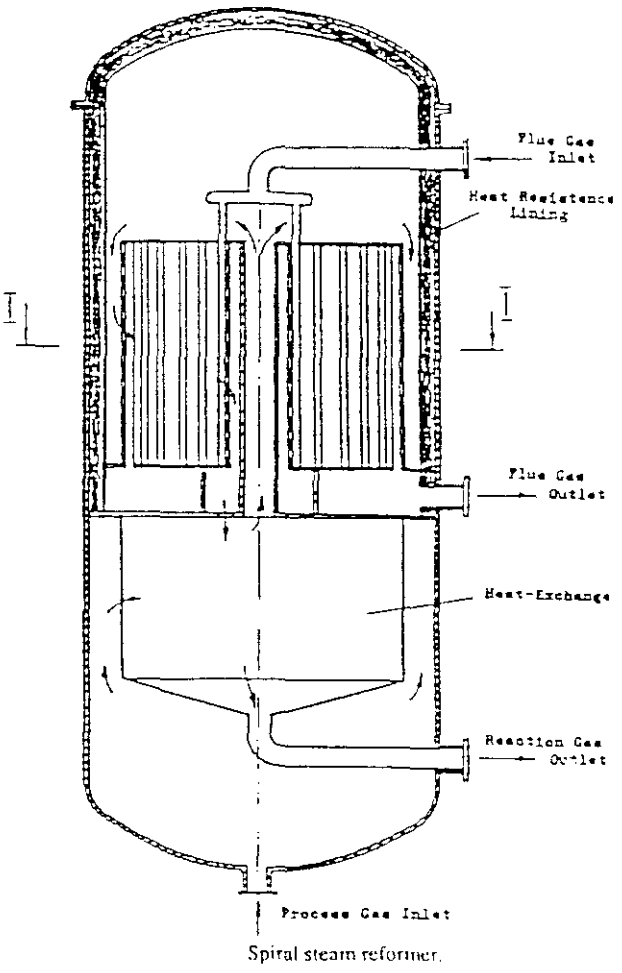


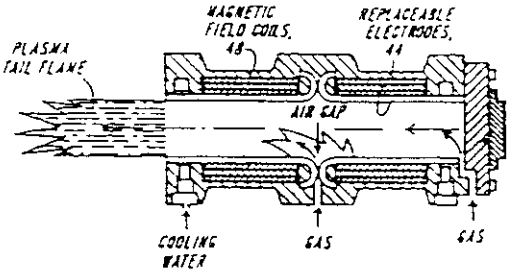
Figure 5.4 (Astanovsky et al, 1992)

5.7 INTERNAL OR DIRECT REFORMING

Internal or direct reformers are defined as those which operate within, or integrated with, a fuel cell or other power generator. The high temperature types of fuel cell, MCFC and SOFC, as described in chapter 3 above, operate at sufficiently high temperatures to reform fuels within, or in a space integrated with, the fuel cell stack. This reduces the stack cooling system and reduces the capital cost of the reforming components. Both heat and steam are provided from the waste products of the fuel cell stack and since the hydrogen is used by the stack as it is formed, this helps in increasing the reaction conversion to hydrogen and carbon dioxide. Molten carbonate fuel cell systems with power outputs from 10 kW and 50 kW using natural gas integrated reformers have been demonstrated (Murahashi et al, 1994). Solid oxide fuel cell systems can reform natural gas without a catalyst and such a system has been demonstrated (Dicks et al, 1995).

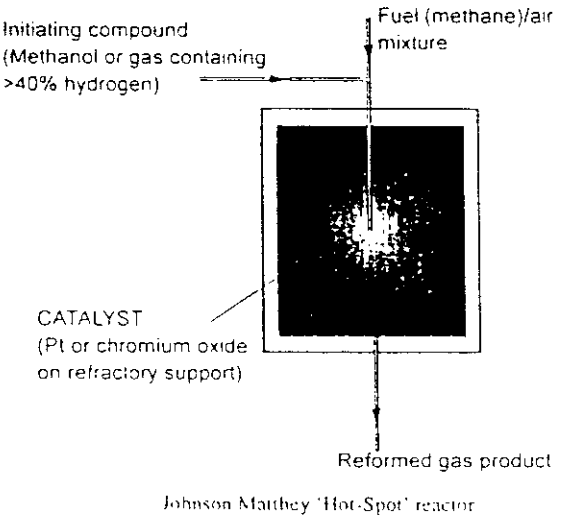
5.8 FUEL PROCESSING FOR TRANSPORT SYSTEMS

This chapter has summarised the various methods of processing hydrocarbon, alcohol and methyl ester fuels to produce a hydrogen rich gas, consisting mainly of carbon dioxide and hydrogen. Some of these are likely to be more suitable for development for use on board vehicles, such as steam reforming and catalytic partial oxidation reforming. However, if compressed gaseous hydrogen or liquefied hydrogen becomes acceptable for widespread use inboard, then the fuel processing could be centralised and the compressed or liquefied hydrogen delivered to main outlet stations. Those fuel processes which are endothermic, and require more than the waste heat from the fuel cell system to produce the hydrogen rich fuel gas, could be activated by burning a small quantity of fuel. Depending upon the operating temperature of the fuel cell, other constituents, such as residual carbon monoxide and fuel carried over from the reactions would need to be removed before the gas is used in a fuel cell. This could be achieved by the use of a selective catalytic oxidiser. Some high temperature cells, operating above about 200^{o}C and which do not contain a platinum catalyst could use



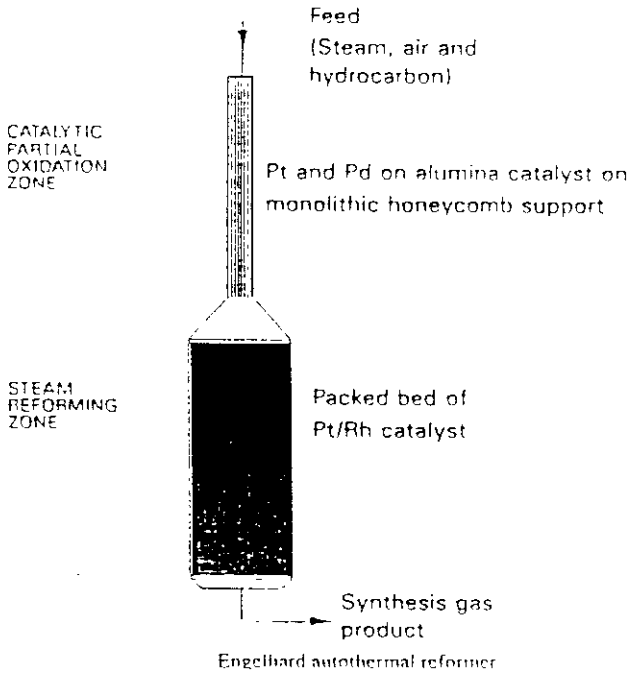
Plasmatron reformer

Figure 5.5 (Bromberg et al, 1995)



Johnson Matthey 'Hot-Spot' reactor

Figure 5.6 (Jenkins, 1990)



Engelhard autothermal reformer

Figure 5.7 (Hwang et al, 1985)

the carbon monoxide as a fuel. In chapter 7 calculations are made of emissions from fuels which are processed to produce the required hydrogen rich fuel gas. These calculations are derived from the chemical equations for the fuel processing and, where fuel is burnt to provide the necessary heat, from published data for fuel combustion (IPCC, 1991 and 1995).

6. ELECTRIC VEHICLES

It was divided into two parts: the first contained the machinery for producing electricity, and the second the machinery that connected it to the screw.
(Jules Verne, 1870, *Twenty Thousand Leagues Under the Seas*).

6.1 INTRODUCTION

Electricity can be applied to various forms of transportation for example, road and rail vehicles, ships and submarines. Any such system would rely on an electric generator to provide the power to an electric motor. Electric generators could be alternating current (ac) or direct current (dc) driven by fossil fuelled steam engines or nuclear powered steam turbines, IC engines or gas turbines using fossil fuels; alternatively, power could be provided by dc photo-voltaic cells, batteries or fuel cells.

In a conventional road transport vehicle driven by an internal combustion (IC) engine, the engine converts chemical energy from a fossil fuel to mechanical energy in a rotating shaft. The necessary vehicle speed/power characteristics for different driving conditions are provided by a geared transmission system to the wheels. Although most of the engine power is used for traction, some is used for auxiliaries such as pumps for the circulation of coolant, for power steering or for vacuum power brakes, and some is used for electrical power generation to recharge the on-board battery and for electrical auxiliaries.

An electric vehicle uses electrical power from an on-board power source which can be a one of a number of systems such as an IC engine electric generator, a battery system re-charged externally or a fuel cell system. Other systems, such as electric trams and railway trains use an overhead or rail system to transfer power to motors inboard the vehicles. The power for overhead power cables or rails could be provided by either conventional or fuel cell power generation stations. Electric motors for traction could

be dc, ac synchronous, ac asynchronous permanent magnet or, in the case of marine application, magnetohydrodynamic where seawater is used as the conducting medium (Adams, 1992). Also, electric motors can be used for regenerative breaking which could be used to rapidly recharge a battery or stored in super capacitors or as kinetic energy in flywheels. This could provide about 20% of the overall vehicle energy consumption (Gover et al, 1996). Fuel cells and the appropriate fuels and fuel processing are summarised in chapters 3, 4 and 5, and batteries in chapter 6.

This thesis concentrates on fuel cell powered vehicles and compares them with IC engines and batteries. In a fuel cell powered vehicle the fuel cell electrochemically converts the chemical energy in a fuel (hydrogen) to direct current electrical energy, without the intermediate conversion to heat and mechanical energy as in an IC engine. The hydrogen fuel can be produced externally and stored in the vehicle, or from an inboard fuel processor which can convert selected fossil fuels into a mixture of carbon dioxide and hydrogen. Some fuel cell types are being developed which can directly process the fuel. The electrical energy can be used or easily converted and controlled for the required speed/power traction characteristics, and for auxiliaries.

6.2 DIRECT CURRENT ELECTRIC MOTORS

Direct current motors are most suited for use with fuel cells and battery vehicles because they operate on dc and can develop high torque at slow speeds or near stationary condition, the latter being particularly important for applications such as icebreaking transport ships. They can be series or shunt wound which are easily controllable by variable resistors or thyristors, respectively.

Efficiencies are between 0.8 and 0.9 and power per unit weight between 150 and 200 Wh/kg (Gover et al, 1996), which can become critical for large powers and limit their use to about 10MW, above which superconducting machines are advantageous, though at present only prototypes have been built. Maximum speed is limited to about 7000 rpm.

Brushes for motors with rotating commutators can be a disadvantage and require regular maintenance. Brush wear is dependent upon the environment and low humidity and/or chemical contamination can give rise to very rapid rates of wear. This can be controlled by the inclusion of chemicals or special materials in carbon brushes during manufacture but unacceptable wear is still experienced occasionally in some applications, particularly at sea.

Conventional permanent magnet direct current motors need a commutator and brushes, which is a rotary switch to rotate the electromagnetic field from the fixed stator coils, to rotate the permanent magnet in the rotor. Brushless permanent magnet direct motors sense and rotate the stator electromagnetic field electronically, thus eliminating the problems of commutation with rotating connecting rings and brushes.

6.3 ALTERNATING CURRENT ELECTRIC MOTORS

Alternating current motors require to be connected via a dc to ac converter in order to be used with fuel cells or batteries.

Alternating current induction motors have a lower production cost than dc types, are almost maintenance free and are now widely used. Efficiencies are between 0.85 and 0.9 and power per unit weight between 200 and 300 Wh/kg (Gover et al, 1996), thus making them more suitable for large powers, but size then begins to become a limitation above 20 to 30MW.

Alternating current synchronous motors employing permanent magnets have efficiencies up to 0.95 and power to weight per unit weight up to 500 Wh/kg (Gover et al, 1996) and are being developed for ship and submarine propulsion. The problems of controlling a synchronous machine and the cost of high performance permanent magnets are disadvantageous in road applications (Gover et al, 1996).

6.4 ELECTRIC RAIL VEHICLES

Electric railways rely upon an external supply of electrical power which is transmitted by either, a conducting rail or overhead cables. The first electrically powered vehicles in 1847 were railway locomotives in the USA (Georgano, 1996). In the UK most electric traction uses series wound dc motors, but since the 1980s three-phase alternating current motors became practicable, and by the early 1990s the latter had been developed for European and Japanese high speed trains (Encyclopaedia Britannica, 1993). Overhead cable electrification now uses 25 kV ac, but in Europe the situation is complicated by different systems. Currently, the service under the English Channel needs to be capable of operating on a 25 kV ac overhead cable system, a 3,000 volt dc overhead cable system and a 750 volt dc conductor rail system.

In principle, fuel cell power supplies could be used to supply any of the above systems, but for high voltage ac systems, both dc to ac conversion and voltage transformation would be necessary; dc to ac conversion because fuel cells generate dc, and voltage transformation because fuel cell stacks need to be built up of individual cells each operating at about one volt. Inboard fuel cell systems to replace diesel engines are a possibility; these would need to carry either compressed hydrogen fuel or a fuel processor to convert a fossil fuel into a hydrogen and carbon dioxide mixture. The analysis of emissions for different systems carried out in later chapters applies to both transport systems and potential fuel cell electric generating stations.

6.5 BATTERY VEHICLES

As mentioned earlier in chapter 2, various types of batteries could be used to power electric drives for transport systems, ranging from those with ambient temperature operation to those which require a high temperature of 300 to 350^{O}C. Low temperature (0-50^{O}C) include lead acid, nickel/cadmium, nickel/iron, nickel/zinc and

zinc/bromine, but the first two are the only currently readily available types. High temperature (290-350^{O}C) batteries include sodium/sulphur, sodium/nickel chloride and lithium aluminium/iron sulphide, but only the first two types are currently serious contenders. In the following, the general information on batteries is from published information ((PA Consulting Group, 1992) and (Gover et al, 1996).

Table 6.1 is a summary table showing the current state of development for each battery type. The details for specific traction systems (PA Consulting Group, 1992) are shown with rated voltages. Energy density in terms of Wh/kg (Gover et al, 1996) is the energy a battery supplies during discharge at constant current. Power density in terms of W/kg (Gover et al, 1996) is the output supplied by a 50% discharged battery at 2/3 of its rest voltage. Efficiency (Gover et al,1996) is the ratio of the energy a battery supplies when completely discharged to the energy supply during recharging.

The use of lead acid batteries for traction in fork lift trucks, delivery vehicles and urban buses is well known and although it has zero emission during usage, emissions are produced at power stations during recharging. The first electrically driven cars were made in the late 19th Century in the USA (Georgano, 1996). According to Gover et al, (1996) the current state of development in battery vehicles is for short range, low power units best suited to urban and fleet applications, with most based on existing vehicle designs. Tables 6.2 to 6.4 from Gover et al (1996) summarise electric cars, light goods vehicles (LGVs) and buses available at that date.

TABLE 6.1 CURRENT STATE OF VEHICLE BATTERY DEVELOPMENT

TYPE	RATED VOLTAGE	CAPACITY (Ah)	STORED ENERGY (kWh)	LIFE (Cycles)	WEIGHT (kg)	RANGE (miles)/ Eff.(%)
Pb/Pb2	93	160	12	800	460	35-50
	216	205	40	800	1200	80-90
	320	42.5	13.5	400		120
			25-33(Wh/kg)		100(W/kg)	70%
Ni/Cd	6	140/190		600	23.5	75-80
	72	55	4	600	140	80-90
			28-50(Wh/kg)		200(W/kg)	70%
Ni/Fe	6.25	200	1.23	1500		
	180	217	39	2500		120
			50(Wh/kg)		100-150(W/kg)	65%
Ni/Zn	6	144	20	360		
Zn/Br2	216	45		500		125
Ni/MH			55(Wh/kg)	>2000	175(W/kg)	80%
Na/S	58.1	300	16.8	900		110-125
	120	160	19.2		183	100-110
			80-105(Wh/kg)		100-150(Wh/kg)	90%
Na/ NiCl2	152	130	27.4	150	336	100-130
Li-Al/ FeS2	24	125	3	>1000		

TABLE 6.2 BATTERY ELECTRIC CARS

	Fiat Panda Elettra	VW City Strommer	Peugeot 106E
Vehicle Wt. (kg)	1390	1690	1275
Motor Type	9.2 kW dc	15 kW dc	ac inducn.
Battery Type	Lead acid	Lead acid	Ni/Cd
Battery wt. (kg)	372		260
Urban Range (km)	60-70	60-80	90-160
Max. Speed (km/h)	70-80	100	90
Cost (£)	11,000	24,000	

TABLE 6.3 BATTERY ELECTRIC LGVs

	Elcat	Ford Ecostar	Conceptor G-van	Bedford CF van
Vehicle Wt. (kg)	1435	1806	3900	3500
Motor Type	13kW dc	56kW ac	dc	40kW dc
Battery Type	Pb acid	Na/S	Pb acid	Pb acid
Battery wt. (kg)	440	360	1270	
Urban Range (km)	60-70	160	100	
Max. Speed (km/h)	70	115	83	
Cost (£)			29,500	

TABLE 6.4 BATTERY ELECTRIC BUSES

	Clean Air Transit	IAD Optare
Vehicle Wt. (kg)	6565	8400
Motor Type	30 kW dc	60 kW dc
Battery Type	Lead acid	Lead acid
Battery wt. (kg)	1862	2280
Urban Range (km)	100	90
Max. Speed (km/h)	64	65

Prototypes designed specifically as electric cars are summarised in Table 6.5, from Gover et al (1996).

TABLE 6.5 PROTOTYPE BATTERY ELECTRIC CARS IN 1995
(Prototype Electric Cars in 1995)

	GM Impact	Nissan FEV	BMW E1
Vehicle Wt. (kg)	1157	900	880
Motor Type	ac inducn.	ac inducn.	ac inducn.
Battery Type	Lead acid	Ni/Cd	Na/S
Battery wt. (kg)	395	200	200
Urban Range (km)	200	250	215
Max. Speed (km/h)	120	130	120

Currently available and prototype electric cars are summarised in Tables 6.6 and 6.7.

TABLE 6.6 CURRENT BATTERY ELECTRIC CARS
(Data from Hutton (1997) and Hunston (1997)

	Toyota Rav 4	Elec. Renault Clio
Motor	Permanent Magnet	22 kW
Battery	Ni/Metal Hydride	
Range (km)	200 urban	60-75 urban
Accn.	0-96 km/h in 18.5s	0-59 km/h in 8.5s
Max. km/h	124	80
Cost (£)	50,000	10,000+ 55 per m. battery lease

TABLE 6.7 CURRENT BATTERY ELECTRIC CARS
(Data from Roberts (1996), Dawe (1997) and Hutton (1997)

	BMW E1	Mercedes Studio A	Ford Ecostar	Peugeot 106	GM EV1
Motor	33.5 kW	40 kW	30 kW		100 kW
Battery	Na/NiCl	Na/Ni/Cl	Na/S	Ni/Cd	Pb acid
Battery (kg)			350		
Range (km)	270	240	160 av.	77	(164 at 77 km/h)
Accn.	0-80 km/h in 12.7s	0-48 km/h in 4.6s			95 km/h in 8.4s
Max. km/h	85	115	112	88	
Cost (£)				12,000	21,000 (lease)

Some of these cars employ regenerative braking, which uses the motor as an electrical generator during braking to recharge the batteries. Although battery cars are now commercially available, they are subsidised and the above costs may not represent the true costs. Apart from the cost, the main problems are the range and recharging time, which could be up to ten hours.

Designs include both rear wheel drive (Figure 6.1) and front wheel drive (Figure 6.2); both Figures are from Roberts (1996).

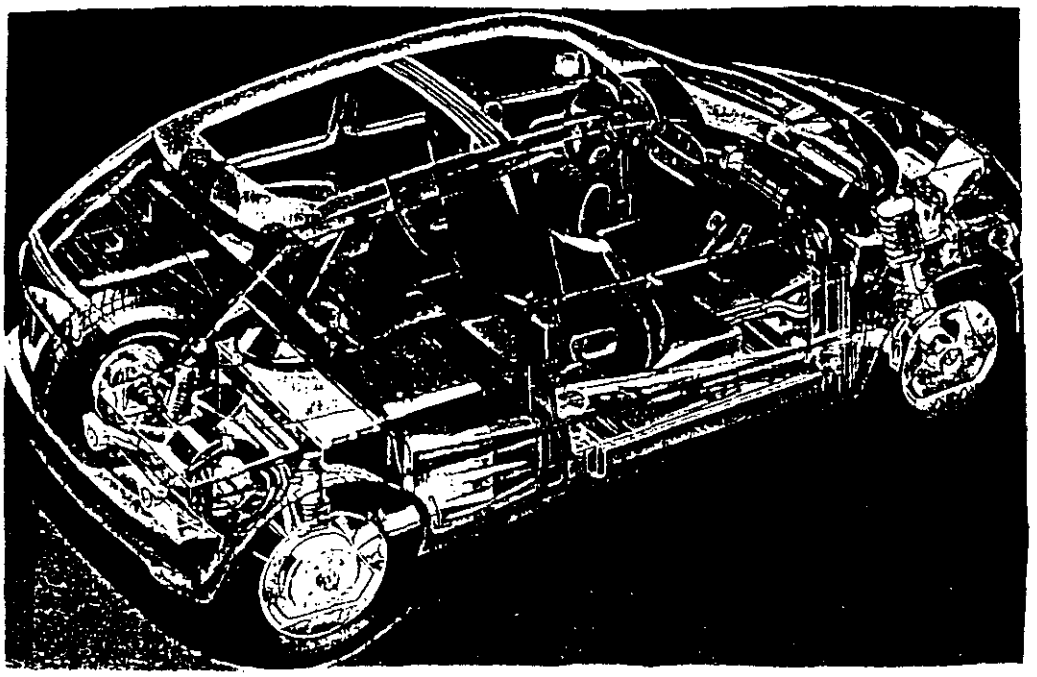


Figure 6.1 BMW E1 Electric Car (Roberts, 1996)

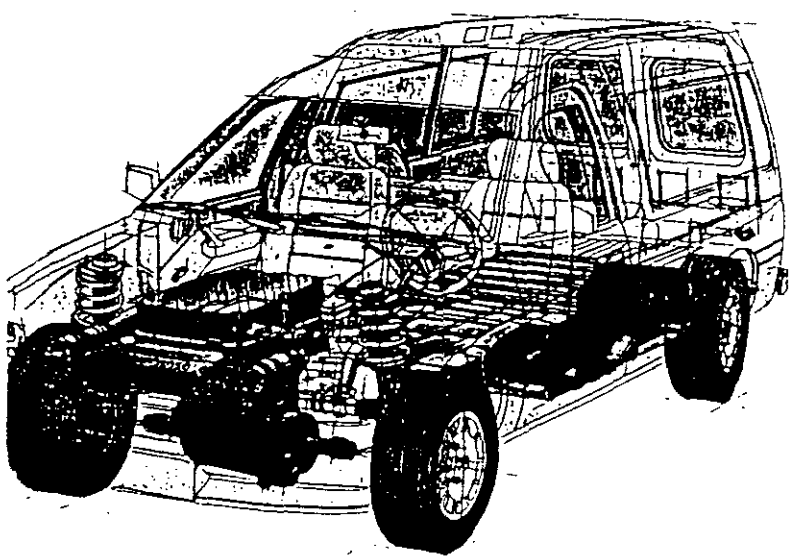


Figure 6.2 Ford Ecostar Electric Van (Roberts, 1996)

6.5.1 BATTERY CHARGING

This section is adapted from published information on the application of batteries to road transport (Gover, 1996).

One of the main disadvantages of battery application in transport systems is the slow rate of recharging compared with the quick refuelling of systems using fuels which are liquid at normal temperature and pressure.

On board chargers can be integrated with, and optimised for the particular battery system in the vehicle, but require a slow overnight charge from the normal domestic electricity outlet. Overnight charging would take 6 to 8 hours and top-up charging could be provided at parking facilities, a system suitable for private electric vehicles.

External chargers have greater flexibility in terms of charging power and hence time, and remove the additional equipment space and weight from the vehicle. They also could be used for overnight charging and top-up charging if facilities are provided at parking areas. Disadvantages are that there is a need to standardise purpose built charging points and hence external chargers cannot be optimised for particular battery systems. This system is best suited for a fleet of vehicles such as for public transport.

Other sources of energy, such as renewable resources, could be considered for recharging battery driven vehicles and these will be included in chapter 7 when emissions from various fuels are calculated. However, the land requirements for renewable energy resources could mean that only small amounts of energy relative to total requirements could be generated. For instance, depending upon the array size, the spacing required for arrays of wind turbines can be as high as 8 to 9 times the diameter (D) of the turbine blades to give high array efficiencies, as shown in Table 6.8 (Johansson et al, 1993).

TABLE 6.8 Typical Wind Turbine Array Efficiencies

Array efficiency (%) compared to equivalent number of turbines with no interference

Array Size	Turbine Spacing 4D	5D	6D	7D	8D	9D
2*2	81	87	91	93	95	96
4*4	65	76	82	87	90	92
6*6	57	70	78	83	87	90
8*8	52	66	75	81	85	88
10*10	49	63	73	79	84	87

Coupled with this, the electrical power generated from wind turbines is typically 500 W/m^2 of wind area, with a potential development of 1000 W/m^2. Thus, to collect large amounts of energy, an array of wind turbines needs to be spread over a wide area and positioned to minimise interference between turbines. However, if winds are seasonally changing in direction then turbines are spaced relatively far apart and the land might be suitable for other uses.

Other estimates for the land requirements for renewable resources (Johansson et al (1993) are given in Table 6.9.

TABLE 6.9 Land Requirements in hectare/MW peak

Photo-voltaic	1.3
Solar thermal electric	4.0
Wind	4.7 to 16
Hydro-electric	16 to 900

The energy and emissions used in recharging battery driven vehicles using various options for power generation will, in chapters 7 and 8, be calculated by the author and compared with those from the manufacture and use of fuels for both internal combustion engine and fuel cell driven vehicles. This will be in the form of amounts of pollutant per kWh developed by the vehicle for a range of vehicle power system efficiency and amounts per kW for a particular range and average speed.

Battery exchange is another approach to providing a rapid form of "refuelling" but batteries need to be standardised and possibly modularised for ease and safety of handling. Again, this system is best suited for a fleet of vehicles with a central servicing point.

One aspect that needs to be addressed when a new technology is introduced on a wide basis, such as for transport, is the possibility of new or increased pollution from the manufacture and disposal of systems. One such potential problem is that lead acid battery cars could produce increased lead pollution in the long term, resulting from inadequate disposal or recycling. However, this problem could be solved by of adequate control of potentially dangerous releases to the environment (Hecht, 1995). Hecht writes that critics of this view consider that mass production of lead acid batteries for cars might cause problems during manufacture and ultimate disposal, and that switching to advanced batteries involves other dangerous materials.

Public response to electric cars has been poor and car manufacturers are unable to meet future mandates for zero emission cars in California for 2% of total sales by 1998 and 10% of sales by 2007 (Jacobson, 1994). Other States in the USA (Massachusetts and New York State) which have adopted similar policies and others which may follow (Sperling, 1996), presumably will be unable to meet such mandates. Consequently, these mandates have been relaxed. However, the introduction of battery driven vehicles could be advanced by the introduction of stricter legislation to reduce pollution from road transportation and power electrical generation. Although this would increase power generation for recharging, mostly

overnight, pollution from this source would be subject to the same legislation and could be reduced by improved exhaust control.

The possibility of introducing fuel cells, already mentioned and to be considered later, by using fuel cell power generation stations to provide the re-charging energy for already proven battery driven vehicles could provide pollution free transport with a significant reduction in carbon dioxide emissions. This possibility would appear to be suitable for a dedicated fleet of vehicles such as city transport buses, and would provide pollution free systems for both power generation and road vehicle use. Also, it would overcome the difficulties of carrying gaseous fuels such as compressed natural gas or compressed hydrogen, or liquid hydrogen at cryogenic temperatures. For fuel cell vehicles using inboard hydrocarbons or alcohol fuels it overcomes the necessity for fuel processing units.

6.6 FUEL CELL VEHICLES

6.6.1 INTRODUCTION

Fuel cell vehicles have been described and compared briefly with IC engine vehicles in section 6.1 above, and some specific examples have been noted in chapter 2. In an IC engine vehicle fuel from a fuel tank is burnt in the engine, and the resulting mechanical shaft energy is transferred via the transmission system through a drive shaft and axle to the wheels. In a fuel cell vehicle, either hydrogen or, a liquid or gaseous chemical or fossil fuel which is converted to a hydrogen gas mixture in a fuel processor, is converted directly to electrical power in the fuel cell. The electrical energy from the fuel cell drives a motor or motors for transferring energy to the wheels, and the power generation is controlled by an overall system monitor and controller. Both IC engine and fuel cell vehicle systems use oxygen in the energy conversions, normally using air. Some specialised systems such as submarines make use of a stored oxidant such as oxygen or a chemical oxidant (Adams, 1989,1990).

development is underway to use alternative fuels such as natural gas, propane, methanol or hydrogen in order to reduce harmful emissions. Fuel cells can, with if necessary the appropriate fuel processor, use any of these alternative fuels with either reduced or near zero harmful vehicle emissions. However, the adoption of an alternative fuel for road transport requires, in the long term, the introduction of a delivery infrastructure for refuelling. The establishment of a fuel distribution network for a new fuel will depend upon sufficient demand to make it economically viable. Also, demand for vehicles which use a new fuel will depend upon the availability of fuel for refuelling at convenient outlets. This situation creates difficulties in the introduction of a new fuel and new vehicles. The situation is made further complicated if the new fuel is gaseous, such as natural gas or hydrogen, requiring safe and relatively bulky storage.

Although this thesis considers and compares the environmental impacts of alternative fuels and technologies in chapter 7, it recognises the difficulties of introducing new fuels by concentrating in chapter 8 on public transport, which could use a dedicated central refuelling depot. Thus, it recognises the need for a strategy to reduce vehicle numbers and enhance public transport. The difficulties in introducing a new vehicle technology, with its incumbent fuel processing or new fuel storage problems, are also recognised in chapter 9 by considering a dedicated fuel cell electric power generation station used to recharge a fleet of battery driven public transport vehicles.

The complexity of fuel processing in fuel cell vehicles depends upon the type of fuel cell, see chapters 3, 4 and 5 for discussions on fuel cells, fuels and fuel processing, respectively. Briefly, this can vary from a separate reformer or other processor for low temperature fuel cells (70^{o}C to 200^{o}C) through integrated reformers or other processors for medium temperature fuel cells (600^{o}C to 700^{o}C) to internal reforming or mixed processing in high temperature fuel cells (900^{o}C to 1000^{o}C). Fuel processing can vary from relatively low temperature steam reforming to higher temperature partial oxidation plus carbon monoxide steam shift. Steam is required for these processes and water for this purpose can be carried inboard or provided from the

fuel cell exhaust, which consists of water and unused gases such as nitrogen and carbon dioxide from the oxygen or air electrode. Unused gases from the input fuel mixture are emitted from the opposite cell electrode to that for water, see chapter 3.

An alternative to fuel processing on board vehicles is to carry out this process centrally at fuel refuelling or storage stations where the fuel may then be converted to pure hydrogen rather than a hydrogen gas mixture, thus also increasing the operating efficiency of fuel cells. This requires a more complex inboard storage for hydrogen either as a compressed gas or a cryogenic liquid. In the near to intermediate future or, according to Gover et al (1996), for the foreseeable future, the primary fuel for transportation is likely to be a fossil fuel. Thus, because of potential logistic and fuel infrastructure problems it is likely that hydrogen for fuel cell vehicles, whether derived from inboard or central processors, will be derived from fossil fuels for some future unknown period.

However, this thesis also considers the atmospheric environmental benefits of providing hydrogen by electrolysis using the current mix of electrical power generating stations, nuclear power stations, or renewable energy resources, see chapter 7.

6.6.2 DEVELOPMENTS IN FUEL CELL VEHICLES

Conceptual car designs (Lemons, 1989) have resulted in a layout where the IC engine is replaced by a PEM fuel cell system consisting of a methanol reformer, fuel cell stack (20 kW/60 kW peak), control systems, transmission and motor controller as shown in Figure 6.3, from Lemons (1989).

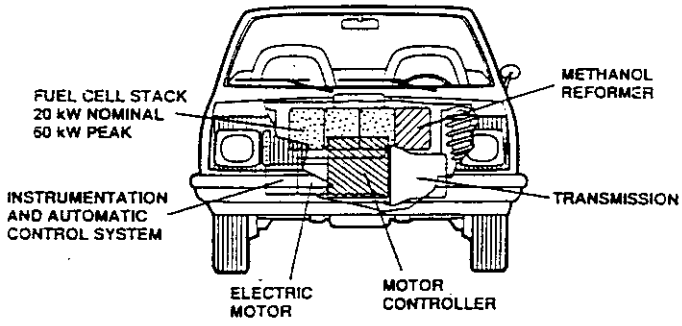


Figure 6.3 Conceptual Fuel Cell Car (Lemons, 1989)

There are a number of subsystems which have to be integrated to produce an effective electric vehicle as shown in Figure 6.4, from Lemons (1989).

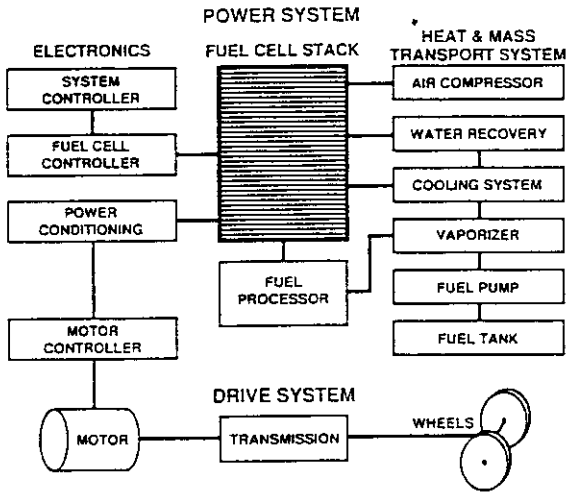


Figure 6.4 Block diagram of subsystems for Fuel Cell Car (Lemons, 1989)

A fuel cell bus project employing liquid cooled phosphoric acid fuel cells is underway in the USA (Kevala, 1990) and the concept consists of a hybrid fuel cell/battery system with methanol and a reformer to supply the fuel cells, as shown in Figure 6.5, from Kevala (1990).

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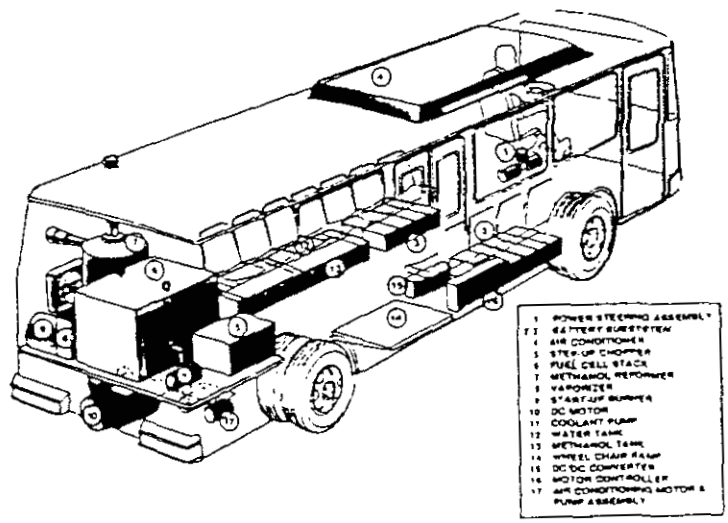


Figure 6.5 Liquid Cooled PAFC/Battery Bus (Kevala, 1990)

Liquid cooled PAFC's are used because of their larger overall efficiency than the gas cooled type and ease of passenger heating. The power source is a 50 kW fuel cell stack, a 132 Ah lead acid battery and a 120 kW (peak) dc traction motor. Energy saving and reduced brake wear is provided by regenerative braking. A similar project is being developed in Japan as shown schematically in Figure 6.6, from Okano (1990).

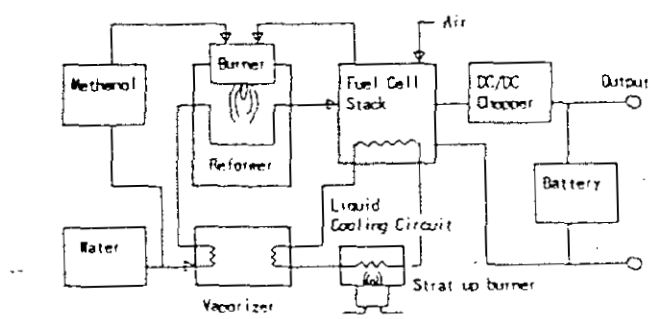


Figure 6.6 Block Diagram of PAFC/Battery Bus Power System (Okano, 1990)

Alkaline fuel cells have been under development for a city bus (Van den Broeck, 1990). However, the company associated with this project and particular design of alkaline fuel cell ceased trading in 1996.

A study for an air cooled PAFC powered bus (Abens et al, 1990) results in a 60 kW fuel cell stack supplied with fuel from an annular bed, integral vaporiser methanol reformer. A 100 Ah polymer bonded electrode nickel cadmium battery is used for peak loads which can be charged directly from the fuel cell stack without the need for a step up dc to dc converter. The lightweight air cooled system provides a 15 minute start up time. Performance and life cycle cost of the power source is claimed to be competitive with conventional diesel engines. The overall concept layout is shown in Figure 6.7, from Abens et al, (1990).

A development programme in the USA for a prototype fuel cell driven vehicle (Creveling and Sutton, 1990) gave a preliminary forecast of vehicle trials in 1996/7, but these have not yet been reported, and current progress is unknown. The first phase envisaged a 10 kW power source using PEM fuel cell stacks and a methanol reformer, as shown in Figure 6.8 from Creveling and Sutton, (1990).

Later phases envisaged the development of a 40 kW power system and the installation of an 80 kW system in a test vehicle. A system analysis for the this system (Vanderborgh et al, 1990) considers both the reformer and overall system elements and their integration. The waste heat is considered to be sufficient to provide *essentially* all of the required input energies; the system efficiency exceeds 55% assuming an 85% hydrogen utilisation efficiency

Direct methanol reforming solid oxide fuel cell systems for transportation applications have been studied (Dees and Kumar, 1990). Other studies have considered the possibility of SOFC's using diesel fuel in marine applications (Adams, 1991). In Dees and Kumar, (1990) the analytical model for the fuel cell stack contains internal fuel vaporiser and heat exchange elements as shown in Figure 6.9. The overall system is shown schematically in Figure 6.10. Performance analysis gives a specific

power of 0.5 kW/kg and a potentially high power density of 2.32 kW/l or 2320 kW/m^3! Overall system performance is estimated to be between 40% and 50%, depending upon the operating power.

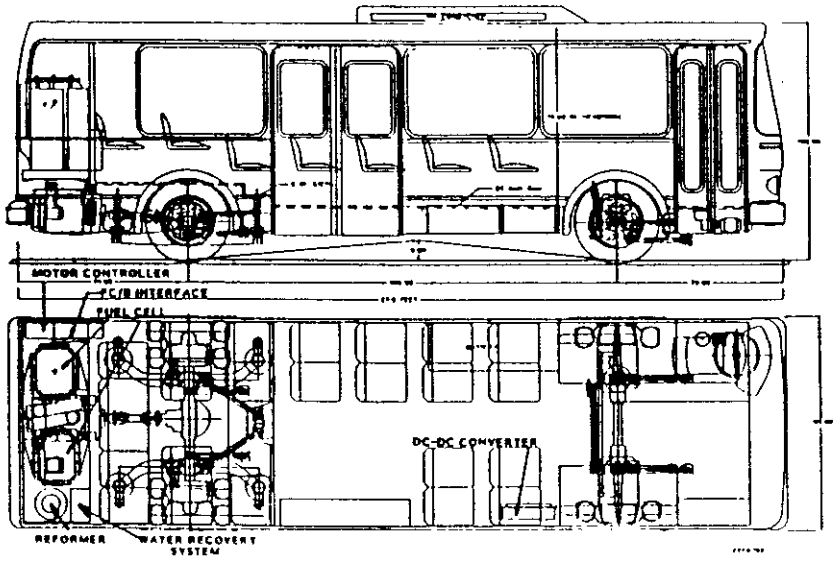


Figure 6.7 Air Cooled PAFC Bus Layout (Abens et al, 1990)

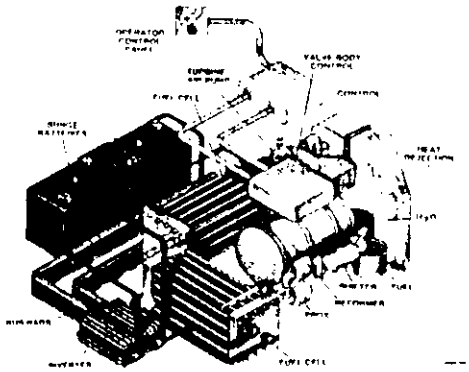


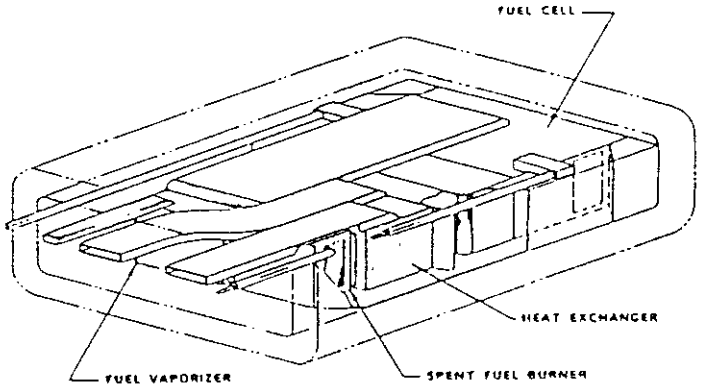
Figure 6.8 10 kW Conceptual Power Source (Creveling and Sutton, 1990)

The Commission of European Countries and the government of Quebec have agreed to make available 100MW of hydropower to produce hydrogen by electrolysis, which will be shipped to Europe for use in the transport and energy intensive industries (Marcenaro, 1992). This has resulted in a project known as the Euro Quebec Hydro Hydrogen Pilot Project (EQHHPP) which promotes the development of industrial applications of hydrogen in Europe. A demonstrator bus has been sponsored by the CEC under this project with industrial partners in Italy and Germany. The concept is

based on a hybrid 35 kW PEM fuel cell stack and 100 Ah lead acid battery system with hydrogen fuel stored as a liquid at about -250^{o}C. Direct current power from the fuel cell stack is conditioned by a dc to dc voltage converter for battery charging or, after being converted to ac, provides power for the traction motor. The general layout for the bus concept is shown in Figure 6.11, from Marcenaro (1992).

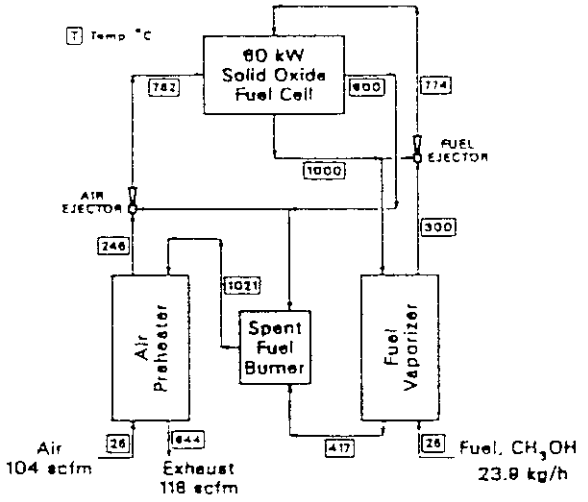
A commercial zero transmission bus has been designed and built by Ballard Power Systems of Canada (Howard and Greenhill, 1993). The prototype vehicle uses a 120 kW PEM fuel cell system with both starter (20 Ah) and auxiliary batteries which do not provide any traction power. It carries gaseous hydrogen as a fuel stored at 3000 psi in aluminium/fibreglass cylinders underneath the floor of the bus, and has a range of 150 km. The traction drive is via a brushless dc motor and the overall layout shown in Figure 6.12.

A later version by Ballard Power Systems (Prater, 1995) employs a 200 kW fuel cell system, providing the same power output as the diesel engine typically installed in the same basic type of bus. It has the same maximum speed and hill climbing capacity as the diesel bus but has improved acceleration. The hydrogen cylinders are stored on the bus roof in a similar configuration to the natural gas version of the basic bus type and it has a range of 400 km. According to Prater (1995) commercialised buses are expected to be available in 1998 following city trials in Chicago. The potential incorporation of regenerative braking increases the range to 560 km. The power supply and prototype of the commercial version are shown in Figures 6.13 and 6.14.



Schematic arranangement of the SOFC system package

Figure 6.9 (Dees and Kumar, 1990)



SOFC system for transportation application

Figure 6.10 (Dees and Kumar, 1990)

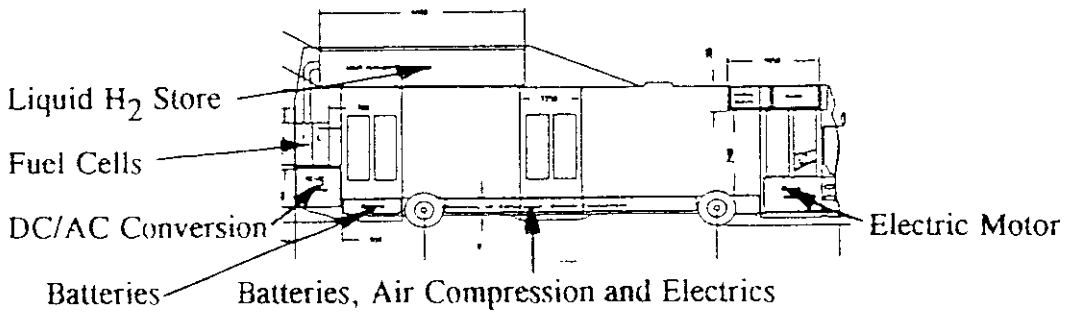


Figure 6.11 General Bus Layout (Marcenaro, 1992)

In Europe , a test vehicle based on a van and using PEM fuel cell from Ballard Power Systems based has been demonstrated by Mercedes-Benz (Lloyd, 1994).
A fuel cell passenger van using PEM fuel cells and hydrogen has been demonstrated by Daimler-Benz (Evans, 1996), as shown in Figure 6.15.

The hydrogen is stored as compressed gas in a specially adapted roof and the fuel cell system contains two 25 kW stacks under the rear seat. The fuel cell system has been jointly developed by Daimler-Benz and Ballard Power Systems, enabling the vehicle to achieve a range of about 250 km and a top speed of 110 km/h. The fuel cell electrodes are made by Johnson Matthey in the UK using techniques which are claimed to be suited to low cost mass production. A later version was unveiled in 1997 and a hydrogen fuelled city bus demonstrator is planned for the future.

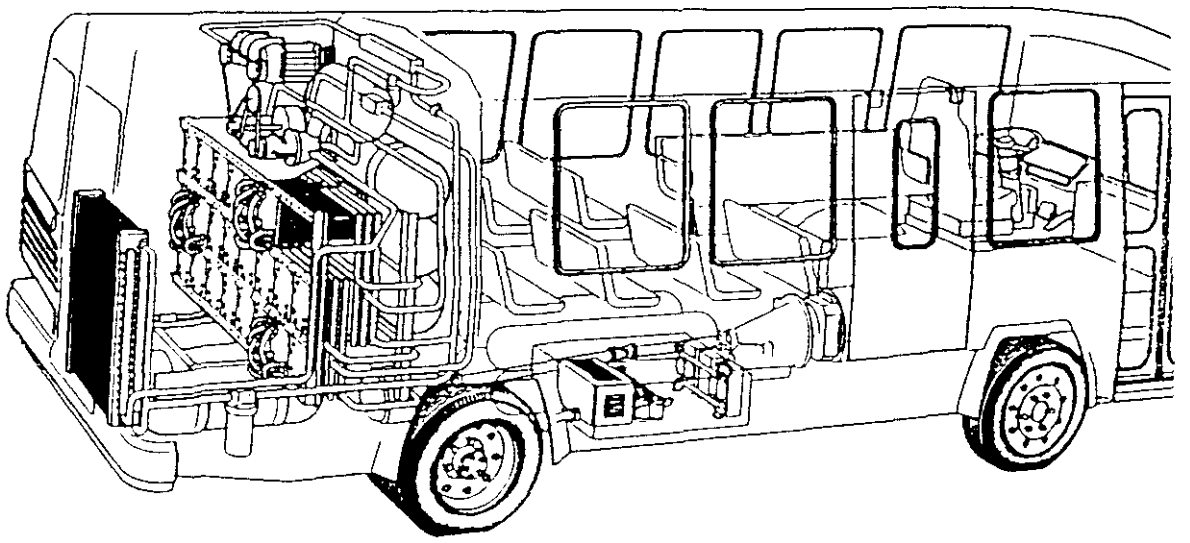
Fuel cell vehicles using hydrocarbon, alcohol or methyl ester fuels might be possible in the future when mobile fuel processing units are developed. This thesis assumes that such development will take place and thus considers a range of fuels for processing in vehicles to produce a mixture of hydrogen and carbon dioxide.

Preliminary results from the current work for carbon dioxide emissions from such systems using different fuels in this way have been published (Adams, 1996a and 1996b). The results calculated later in chapter 7 update these by including later data on energy and emissions from the production of fuels, as well as calculating emissions of other pollutants.

The Chrysler Corporation have in the USA issued reports of two fuel cell car concepts. The first concept, shown in Figure 6.16 (Borroni Bird, 1995), has PEM fuel cells and high pressure hydrogen gas storage tanks.

The second, in a joint concept by Chrysler, Ford Motors and General Motors, envisages an inboard fuel processor which could use a range of fuels, and reported in the Autocar (Scarlett, 1997), and shown in Figure 6.17. The system envisages fuel vaporisation, partial oxidation to produce hydrogen and carbon monoxide, a water

shift reaction similar to that used in fuel reforming to convert the CO to carbon dioxide and produce further hydrogen, and selective oxidation of the remaining carbon monoxide. These processes are described in chapter 5, above. The article by Scarlett, (1997) indicates that the PEM fuel is pressurised at 20 to 30 psi.7.7



Fuel Cell Bus System Layout

Gradability	Start on 20% Grade
	Maintain 30 km/h (20 mph) on 8% Grade
Acceleration	0 - 50 km/h (0 - 30 mph) in 20 sec
Top Speed	70 km/h (45 mph)
Range	150 km (94 mi)
Meets Urban Mass Transit Authority (UMTA) Performance Criteria	

Figure 6.12 PEM Fuel Cell Bus Layout (Howard and Greenhill, 1993)

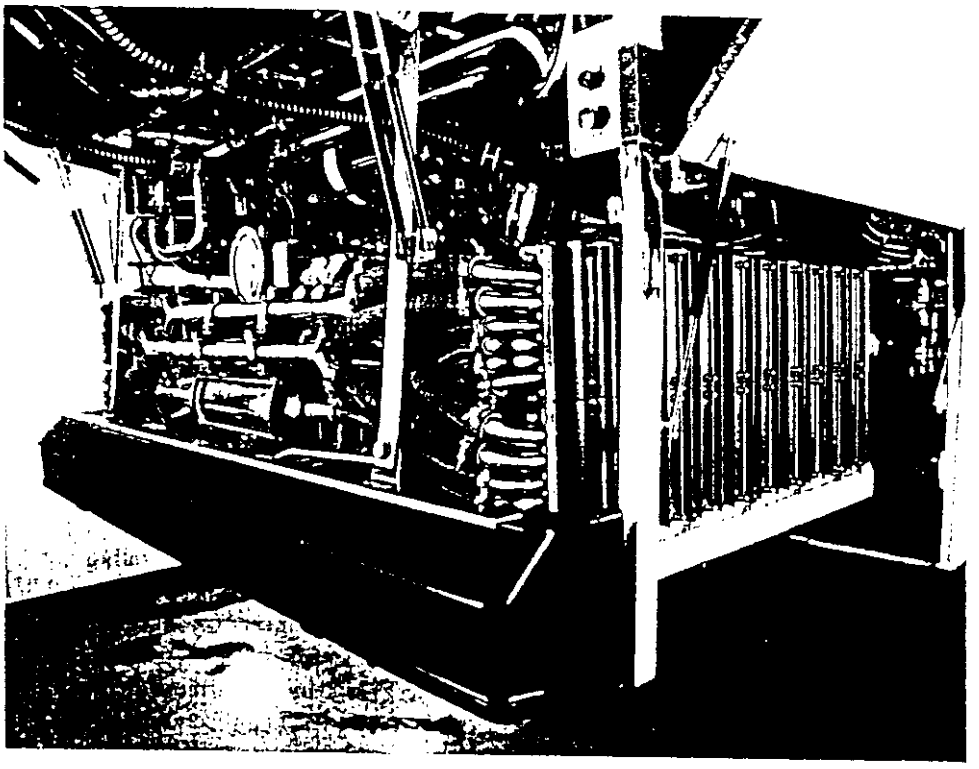
Recently, (Matthews, 1997), a British led company (Zevco) has tested a van, converted from battery to an alkaline fuel cell drive using compressed hydrogen fuel. The company which developed these cells, Elenco in Belgium (Van den Broeck, 1990), ceased trading in the early 1990s and was aquired by Zevco.

The first fuel cell driven car using reformed methanol to produce hydrogen (Figure 6.18) has been demonstrated (Toyota, 1997) and is based on the RAV 4 electric car (Table 6.6). It has a maximum speed of 125 km/hr, a 500 km range and a maximum power of 50 kW with a 25 kW fuel cell. The PEM fuel cell has a length/width/height of 1080/500/240 mm and the metanol reformer is 300 mm long and 600 mm diameter.

6.7 SUMMARY

Although battery driven vehicles are commercially available they are costly, have a limited range and require relatively long recharging periods. They are more suitable for specific applications such as a fleet of urban vehicles or for public transport.

Fuel cell vehicles have been demonstrated but are more costly than battery vehicles. Public acceptance is probably dependent upon the acceptance of hydrogen a fuel. Although safe storage of compressed hydrogen has been developed and demonstrated, there is still a need to convince Governments and the public that it is a safe fuel. The development of systems which could use conventional liquid fuels would circumvent this problem, but the inboard processing of petrol or diesel requires considerable development. Although pilot projects are underway, fuel cell systems are unlikely to be competitive with IC engines until legislation for clean exhausts is implemented.



Compact 200 kW (275 hp) PEM fuel cell engine which powers Ballard's full size prototype transit bus.

Prototype of the commercial zero-emission transit bus powered entirely by a 200 kW PEM fuel cell power plant

Figures 6.13 and 6.14 (Prater, 1995)

Later sections of this thesis consider options for introducing fuel cells to the transport sector, and conclude that the development of electrical power generation stations for battery recharging or the supply to overhead cable or electric rail systems might be the best way to proceed. In this way, conventional fuel such as natural gas or diesel fuel could be used to generate the electrical power, and projects would help to reduce the production costs of fuel cells. Whether or not this would assist in developing fuels cells for vehicles is dependent upon the type of fuel cell used. However, the ideal fuel cell is one which can internally reform a hydrocarbon fuel such as the solid oxide type; internal reforming gives the least pollution (see later in Chapter 7).

Figure 6.15 (Evans, 1996)

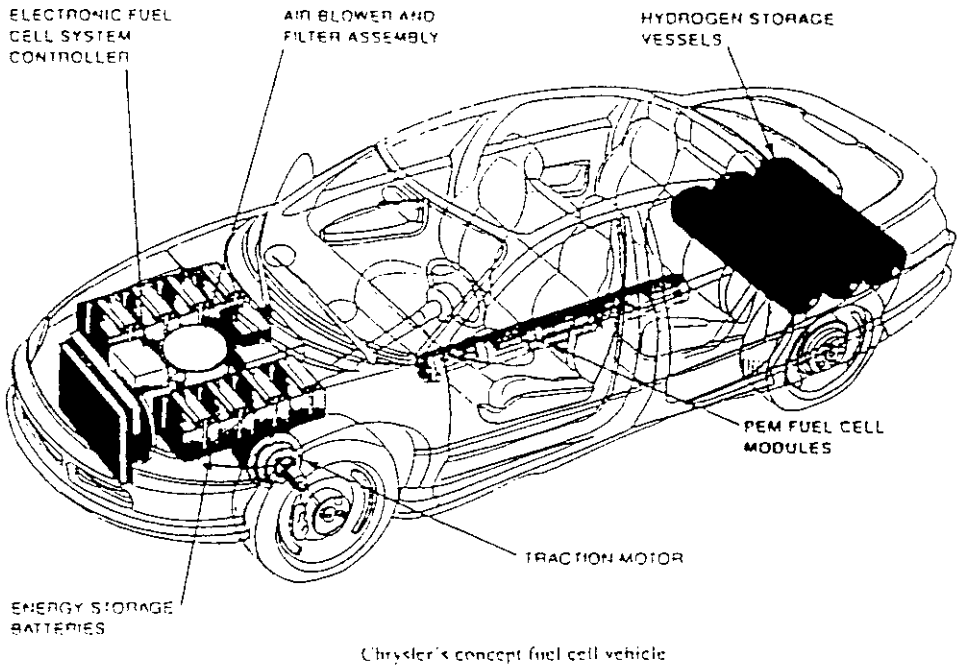


Figure 6.16 (Borroni-Bird, 1995)

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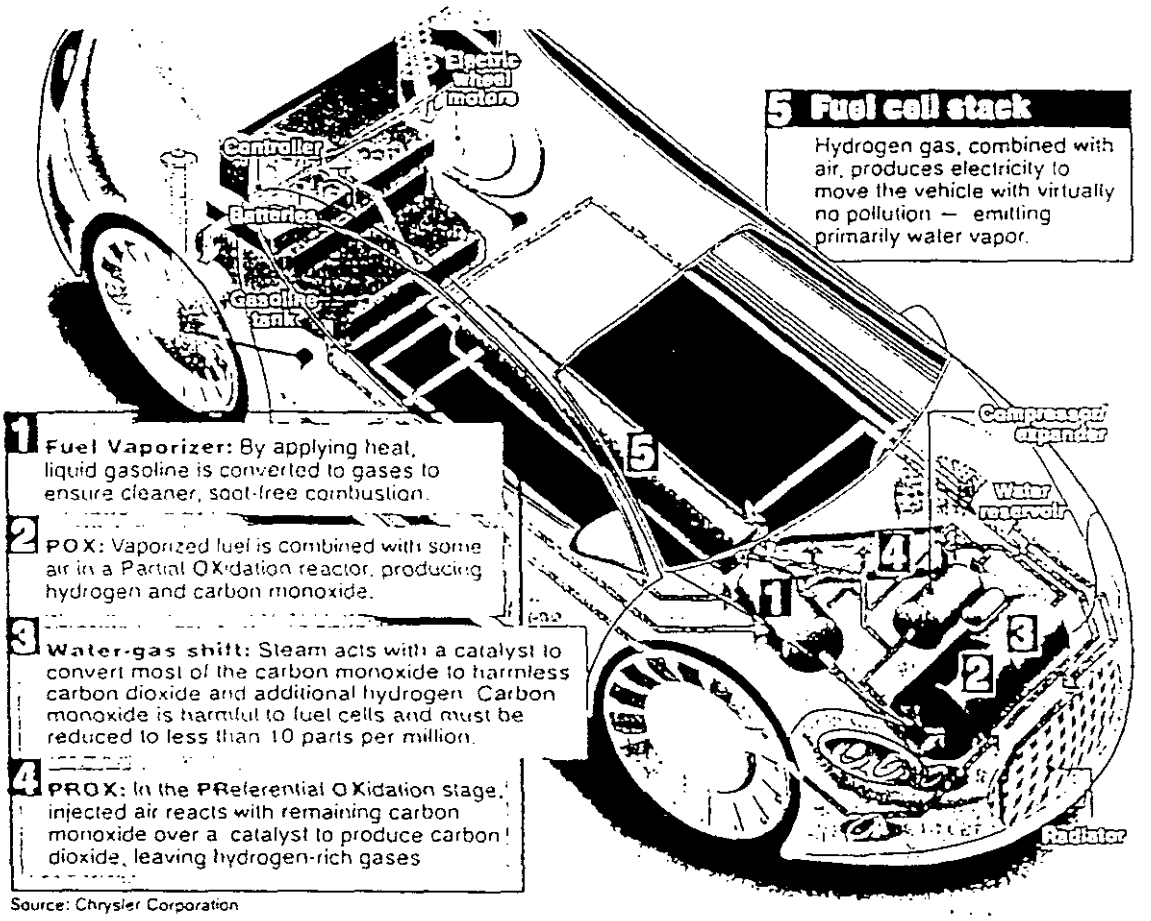

Figure 6.17 Chrysler Multi-fuel Fuel Cell Car Concept
(Autocar, 1997)

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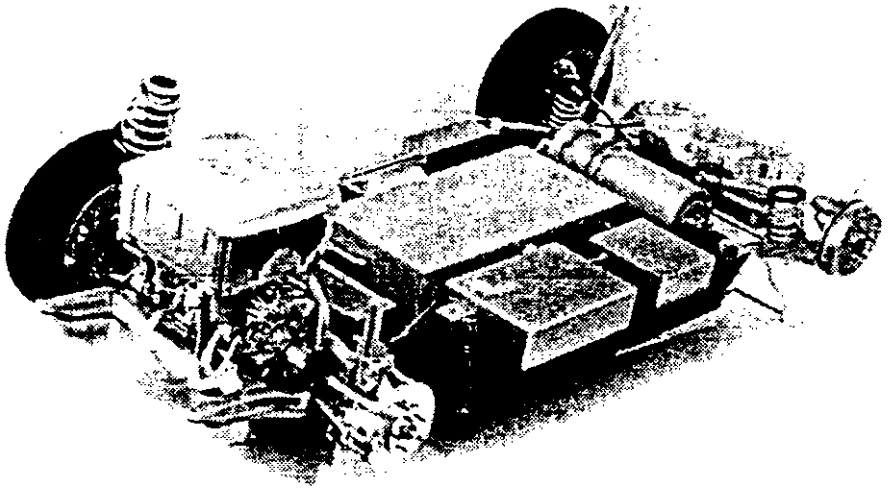

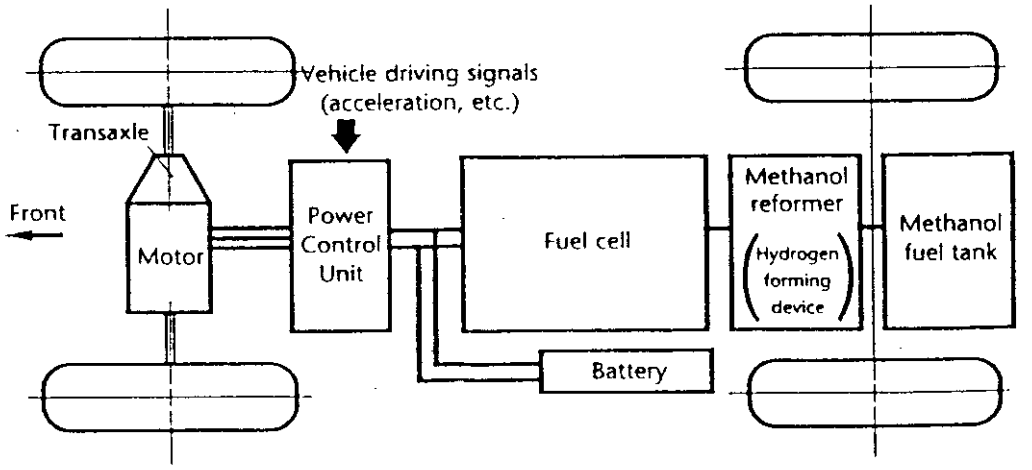

Figure 6.18 Toyota PEM Fuel Cell Car

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7. ENERGY CONSUMPTION AND EMISSIONS

Motor vehicles generate more air pollution than any other single human activity. (M P Walsh, 1989, *Motor Vehicles and Global Warming).*

7.1 INTRODUCTION

This chapter details the calculations made by the author, some from published data and some from first principles, for the energy and emissions used during the production and use of fuels for the transport sector. Energies and emissions are calculated as quantities per kWh of energy developed by a power system. Transport systems considered are IC engines of a size suitable for public transport systems, fuel cells and rechargeable batteries. The calculations are made using SuperCalc 5 Spreadsheet software, using the equations detailed later in this chapter, for the following parameters and a range of fuels:

(a) fuel consumption,

(b) energy consumption during fuel production, usage and the resultant total,

(c) emissions during fuel production, usage and the resultant total,

for IC engines and fuel cells, and:

(d) emissions produced during battery recharging,

for battery driven vehicles.

The fuels considered are hydrogen, petroleum, diesel fuel, natural gas (mainly methane), liquid petroleum gas (mainly propane), methanol, ethanol and rape methyl ester (RME). Methanol and ethanol are named biomethanol and bioethanol when produced from biomass sources.

It should be noted that the calculations for fuel cells are applicable to both the transportation and power generation sectors.

Energy and emissions which can be expected from the production and use of fuels depend upon the type of fuel and power unit being employed. The major emission, in terms of volume or mass, is carbon dioxide and is important in that it is a major greenhouse gas, giving rise to global warming, see chapter 1. Other pollutants, such as carbon monoxide, methane and nitrogen oxides also contribute to global warming as well as being a health hazard. Others which constitute a health hazard are non methane volatile organic compounds (NMVOCs) and particulates or particulate matter (PM) such as soot, see chapter 1.

Comparisons, in terms of the amount of energy used and the amount of emissions to the atmosphere, are made for the various fuels during their manufacture and usage. Calculations for vehicle power system manufacturing phases can only sensibly be made for a particular size of vehicle, and this is deferred to chapters 9 which considers through life studies for public transport vehicles. During fuel production, energy is used and emissions produced during the various phases, and during the usage of the systems energy is used as fuel. Battery vehicles use energy during their recharging phase.

The proton exchange membrane fuel cell type would be the best solution for vehicles because of size limitations in installation; see chapter 3, above, for a comparison of weights and sizes of all types. Solid oxide fuel cells have the potential for similar sizes, but further development is needed. It is possible that alkaline fuel cells could be used in vehicles, but because of their sensitivity to carbon dioxide these are considered to be unsuitable, except where pure hydrogen and oxygen would be used as the fuel and oxidant. Phosphoric acid fuel cells, because of their potentially lower cost could

be considered where space is not at a premium, such as in railway locomotives.

7.1.1 INTERNAL COMBUSTION ENGINES

Fuel consumption for IC engines is calculated, using the lower heating values for the above fuels, for a range of efficiencies (0.2 to 0.45) appropriate for this technology. The theoretical efficiency, assuming no heat losses and that air is the working gas with no change in specific heat with temperature, is 0.46 for petrol and gas engines and 0.56 for diesel engines. However, the working gas is a mixture which differs before and after fuel ignition and the individual gases have specific heats which vary with temperature. When account is taken of the variation in the working gases, heat losses give an actual efficiency of about 50% to 80% of the theoretical efficiency (Roberts and Miller, 1958). Thus, the range 0.2 to 0.45 is considered to be more than adequate to encompass the efficiencies of IC engines.

The lower heating values are chosen because the enthalpy of condensation of the exhaust gases is unavailable in IC engines (Sweeden and Kerr, 1976). Also, these are recommended and used to calculate estimations of greenhouse gas emissions and sinks Internationally (IPCC, 1991 and 1995). Higher heating values of fuels, as representing their energy content, are used to calculate the fuel energies used over the same efficiency range of 0.2 to 0.45.

Data on the emissions produced from the exhaust of IC engines are taken from published data (IPCC, 1991 and 1995) for various fuels. The fuels considered using this data are petroleum, diesel fuel, natural gas (mainly methane), liquid petroleum gas (mainly propane) and methanol. Other published data (Gover et al, 1996) is used for emissions using ethanol and rape methyl ester (RME).

7.1.2 FUEL CELLS

In order to carry out the required calculations, certain basic data is required on the

performance and manufacture of fuel cells. Information was sought from fuel cell manufacturers on efficiency or fuel consumption and quantity of materials used in manufacture. The replies indicated that efficiencies or fuel consumption varied widely between different manufactures and under different operating conditions, even for the same type of fuel cell. Some manufacturers, particularly those considered to be important in the development of proton exchange membrane fuel cell types, declined to provide information on both performance and materials.

Given these difficulties and restrictions on information, the design of the research project had to be adapted. In consequence, fuel consumption is calculated, for the fuels listed in paragraph 7.1 (hydrogen, petroleum, diesel fuel, natural gas, LPG, methanol, ethanol and RME), for a range of fuel cell efficiency (0.2 to 0.8) using the fuel lower heating values. Higher heating values of fuels are used to calculate the fuel energies during usage over the same efficiency range of 0.2 to 0.8.

These calculations for fuel consumption, energies used and emissions produced are applicable to the use of fuel cells in both the transportation and power generation sectors.

7.1.3 RECHARGING BATTERIES

Electric vehicles using batteries have zero emission during usage, but emissions are produced from the electrical generating stations used to provide energy during the recharging phase. These emissions are calculated for a range of battery efficiency (0.6 to 0.85) taking into account both a charging efficiency and a mix of power stations, as follows.

The emissions produced during recharging using the current mix of electrical generating stations are calculated using published data for the emissions produced from power stations (Gover et al, 1996) and the latest data for the current mix of electric power stations, (DTI, 1995).

It has been stated in chapter 2 that this project recognises the need to reduce congestion of road transport by applying the results to public transport. This includes the potential for using fuel cell electrical generation to provide the energy for recharging battery driven vehicles such as fleets of buses. Thus, emissions produced if fuel cell power stations are used for recharging batteries are calculated from first principles using the chemical equations for the fuel reforming processes.

7.2 FUEL CONSUMPTION

7.2.1 FUEL CELLS USING HYDROGEN

As already explained, because of the lack of information from fuel cell manufacturers, specific hydrogen consumption (kg hydrogen/kWh) is calculated for a range of efficiency. In accordance with accepted practice for calculating fuel energy (IPCC, 1991 and 1995) this calculation uses the lower heating value for hydrogen as follows:

$$\text{Efficiency, } n = \text{Power/ Lower Heating Value} \quad [1]$$

The lower heating value of hydrogen is 119,930 kJ/kg, hence:

$$n = \text{Power in kW}/119{,}930/(\text{kg hydrogen/sec}) \quad [2],$$

hence, the specific fuel consumption is given by:

$$\text{kg } H_2/\text{kWh} = 3{,}600/119{,}930/n = 0.03002/n \quad [3].$$

This is calculated for efficiencies from 0.2 to 0.80, based on the efficiency range for practicable fuel cells discussed in chapter 3.

7.2.2 FUEL CELLS USING REFORMED FUELS

In order to calculate the consumption for reformed fuels, when the fuel cell uses a mixture of hydrogen and carbon dioxide or hydrogen if the reformate is purified, use is made of the of the chemical equations for the overall reforming reactions given in chapter 5 above. The main difference between using a reformate fuel of hydrogen plus carbon dioxide and pure hydrogen is that a fuel cell will operate at a higher efficiency on pure hydrogen. The calculations are now described for the various types of fuel: saturated hydrocarbons, rape methyl ester (RME) and alcohols

For saturated hydrocarbons:

$$C_nH_{(2n+2)} + 2nH_2O \longrightarrow (3n+1)H_2 + nCO_2 \quad [4]$$

and using the gramme molecular weights,

$$(14.026n+2.016)C_nH_{(2n+2)} + 36.032nH_2O \longrightarrow (6.048n+2.016)H_2 + 44.01nCO_2 \quad [5]$$

the ratio hydrocarbon fuel/hydrogen consumption is $(14.026n+2.016)/(6.048n+2.016)$. However, this does not take into account the heat of reformation and only applies where this heat is provided externally or for fuel cells which can internally reform fuels, such as the solid oxide type. For low temperature fuel cells, the heat of reformation needs to be provided by burning an additional amount of fuel. This is assumed to be an additional 10% of that consumed by the fuel cell (Virji et al 1995, Dicks 1995 and Hohlein et al 1995). Hence, the ratio

hydrocarbon fuel/hydrogen consumption then becomes

1.1(14.026n+2.016)/(6.048n+2.016).

The higher hydrocarbon fuels are fractional distillates from crude oil and in order to carry out the above calculations there is a need to determine their chemical formula.

Petrol consists of distillates with boiling points from 70°C to 200°C ie, mainly heptane (C_7H_{16}) with other hydrocarbons up to up to decane ($C_{10}H_{22}$). For the purpose of calculating fuel consumption in fuel cell systems using reformed petrol, the chemical formula for desulphurized petrol is assumed to be C_7H_{16}.

Diesel fuel has the following chemical composition by weight (RAE Cobham, 1990):

(a) 65.4% to 69.25% hexadecane ($C_{16}H_{34}$),

(b) 31.35 to 34.6% total of xylene (C_8H_{10}) and napthalene ($C_{10}H_8$),

(c) 0.28% to 1.07% sulphur, mainly as dibenzothiophene ($C_{12}H_8$).

For the purpose of calculating fuel consumption for, and later carbon dioxide emission from, fuel cell systems using reformed diesel fuel , the chemical formula of desulphurized diesel fuel is assumed to be $C_{16}H_{34}$.

For Rape Methyl Ester (RME), using the chemical formula and reforming reaction assumed in chapter 5:

$$C_{19}H_{38}O_2 + 36H_2O \text{ ----> } 55H_2 + 19CO_2 \quad [6]$$

and using the gramme molecular weights, the RME/hydrogen consumption is 298.49/110.88 = 2.692 for internal reforming or, 1.1*298.49/110.88 = 2.9612 for external reforming.

For methanol:

$$CH_3OH + H_2O \longrightarrow 3H_2 + CO_2 \quad [7]$$

and using the gramme molecular weights, the methanol/hydrogen consumption is 32.042/6.048 = 5.298 for internal reforming or, 1.1*32.042/6.048 = 5.828 for external reforming.

For ethanol:

$$C_2H_5OH + 3H_2O \longrightarrow 6H_2 + 2CO_2 \quad [8]$$

and using the gramme molecular weights, the ethanol/hydrogen consumption is 46.068/12.096 = 3.8085 for internal reforming or, 1.1*46.068/12.096 = 4.1894 for external reforming.

7.2.3 FUEL CELLS USING PARTIAL OXIDATION OF FUELS

In order to calculate the consumption of partially oxidised saturated hydrocarbons, the overall reaction for partial oxidation plus the carbon monoxide shift reaction given by equation [8] in chapter 5, is used:

$$2C_nH_{(2n+2)} + nO_2 + 2nH_2O \longrightarrow (4n+2)H_2 + 2nCO_2 \quad [9].$$

Using this equation and gramme molecular weights, the hydrocarbon fuel/hydrogen consumption is (26.036n+2.016)/(8.064n+2.016).

For RME, equation [20] in chapter 5 is used:

$$2C_{19}H_{38}O_2 + 17O_2 + 38H_2O \longrightarrow 76H_2 + 38CO_2 \quad [10]$$

Using this equation and gramme molecular weights, the RME/hydrogen consumption is 596.99/153.22 = 3.896.

7.2.4 INTERNAL COMBUSTION ENGINES

The above calculations for reformed fuels also apply to internal combustion engines using hydrogen or a hydrogen rich gas reformate as a fuel, the main difference being that a different range of efficiencies is applicable.

Similar calculations to those in paragraph 7.2.1 above, using lower heating values, are made for the use of the various fuels (petroleum, diesel, methane, propane, methanol, ethanol and hydrogen) in internal combustion engines, but for a different efficiency range (0.2 to 0.45). At the appropriate efficiencies, those for petroleum, diesel, methane and methanol are found to compare well with published data (IPCC, 1991, 1995), including that from a manufacturer of diesel and natural gas engines (Cummins, 1994).

7.2.5 RESULTS

Results for both fuel cells and IC engines are plotted against efficiency in Figures 7.1 to 7.3, and the complete results are given in Table A.1 in Appendix A. The results are plotted in three bands, .04 to 0.4 kg /kWh in Figure 7.1, 0.1 to 0.8 kg/kWh in Figure 7.2 and 0.1 to 1.0 kg/kWh in Figure 7.3. This banding has been chosen to split the results where they are very close in value for different fuels.

Figure 7.1 shows that hydrogen, having the highest heating value of all the fuels, has the lowest specific consumption in both IC engines and fuel cells. It also shows that methane, having the highest heating value of the fossil fuels has the lowest specific consumption. The alcohols ethanol and methanol, having the lowest heating values of the fuels considered, have the highest specific consumption (FigureS 7.2 and 7.3).

Specific fuel consumption for 50-60% efficient fuel cells and 30-35% efficient internal combustion engines, in descending order, are:

methanol in IC engines,

ethanol in IC engines,

RME in IC engines,

diesel in IC engines,

petrol in IC engines,

propane in IC engines,

reformed methanol in fuel cells,

internally reformed methanol in fuel cells,

reformed ethanol in fuel cells,

methane in IC engines,

internally reformed ethanol in fuel cells,

partially oxidised RME in fuel cells,

partially oxidised diesel fuel in fuel cells,

partially oxidised petrol in fuel cells,

partially oxidised propane in fuel cells,

reformed diesel in fuel cells,

reformed RME in fuel cells,

internally reformed RME in fuel cells,

partially oxidised methane in fuel cells,

reformed petrol in fuel cells,

reformed propane in fuel cells,

internally reformed diesel in fuel cells,

internally reformed petrol in fuel cells,

reformed methane in fuel cells,

internally reformed propane in fuel cells,

internally reformed methane in fuel cells,

hydrogen.

Partially oxidised fuels have greater specific fuel consumption than the same reformed fuels because partial oxidation produces less hydrogen per mole of fuel than reforming.

Figure 7.1 Fuel Consumption for Fuel Cells

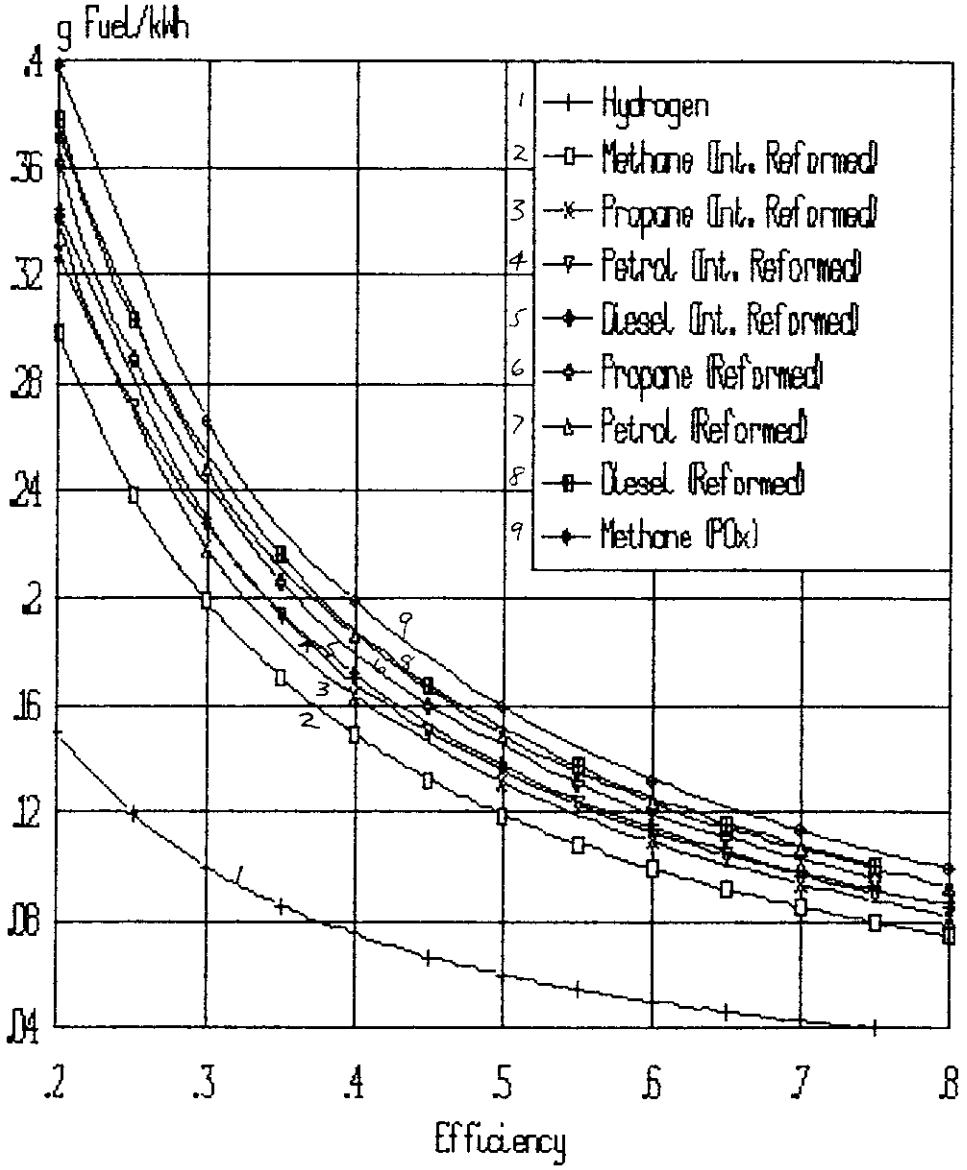


Figure 7.2 Fuel Consumption for Fuel Cells

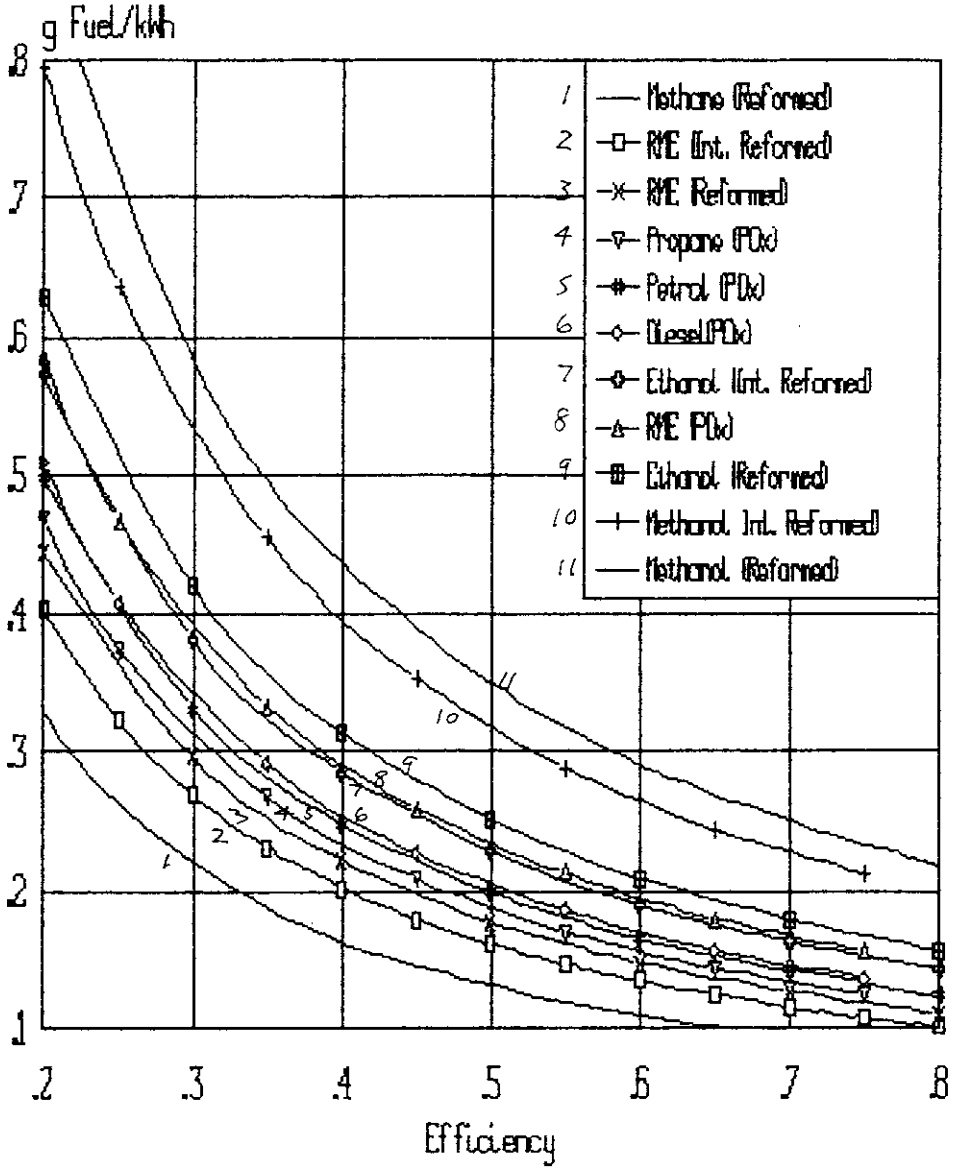
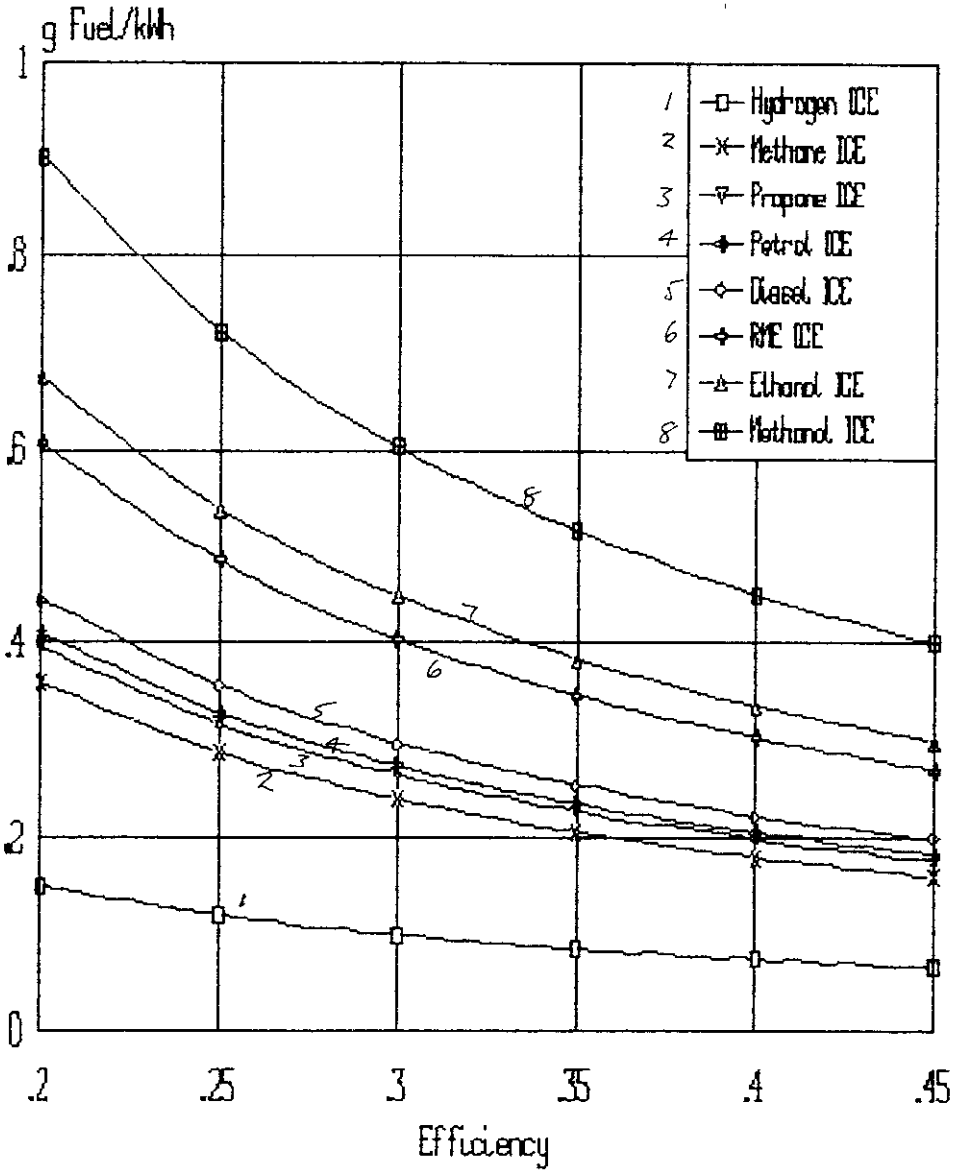


Figure 7.3 Fuel Consumption for Fuel Cells



Externally reformed fuels have greater specific fuel consumption than internally reformed fuels because additional fuel is used to provide the heat for the endothermic reaction. These processes are described in chapter 5.

7.3 ENERGY AND EMISSIONS FROM FUEL PRODUCTION

7.3.1 INTRODUCTION

The energy used, and pollutants emitted from, the production of fuels must take into account all the manufacturing processes from drilling operations through to delivery to the customer, including those due to any fuels burnt and the electrical power generation used.

As described in chapter 2 there have been several publications on the environmental aspects of fuels, including the energy used in production. However, only two include energy consumption in a full energy life cycle analysis (PA Consulting Group, 1992) and (Gover et al, 1996). The first (PA Consulting Group,1992) considers:

(a) a specific car engine (Volkswagen Golf) using petrol,

(b) the average mix of electricity power generation stations in 1989 for recharging battery systems,

(c) pure hydrogen as the fuel for fuel cells,

(d) an overall figure of 83.1% for the amount of energy content of crude oil in the ground which remains in petrol when it reaches a car (Boustead and Hancock, 1979),

(e) an overall figure of 65% for the efficiency with which hydrogen can be produced from coal or natural gas (Boustead and Hancock, 1979), resulting

in an overall efficiency from raw materials in the ground to electrical energy output from the fuel cell,

(f) emissions in terms of CO_2-Equivalents, as described in chapter 2.

The second (Gover et al, 1996) considers:

(a) a range of fuels (petrol, diesel, liquefied petroleum gas (LPG), natural gas, biomethanol, bioethanol and biodiesel) for internal combustion engine vehicles,

(b) electricity using the average power station mix for 1991 and 1995 (based on 1993 estimate) for recharging battery driven electric vehicles,

(c) energy use and flaring on oil and gas drilling platforms and terminals,

(d) transport of crude oil by pipeline and ship assuming 75% originates from the North Sea and 25% from the Middle East,

(e) a fluid catalytic cracking plant is typical in the UK,

(f) petrol, diesel, LPG and natural gas are transported by pipeline to storage terminals and then to filling stations by large road tankers. The energy to compress natural gas has been neglected and losses are assumed to be 1%,

(g) the fuel used by agricultural machinery for the production of biofuel crops,

(h) for biofuels, by-product energy credits for straw and cattle feed,

(i) transport of feed stocks is by conventional road vehicles,

(j) processing of raw materials using primary energy values for the materials, heat and power,

(k) distribution of final product by diesel road tanker.

(l) emissions in terms of g/GJ of fuel energy.

For the present thesis, the energy and emissions from the production of:

(a) fossil fuels and biofuels (biomethanol, bioethanol and RME) are from the latest published data which uses absolute units (Gover et al, 1996) rather than CO_2-Equivalents (PA Consulting, 1992), plus allowance for the compression of gaseous fuels, as detailed in sections 7.3.2 to 7.3.7 below,

(b) methanol by non-biological industrial methods are calculated from published data for energy used (ETSU, 1994a), and from first principles using the chemical equations for the processes involved for the emissions, as detailed in section 7.3.5 below,

(c) hydrogen by electrolysis are calculated from published data for energy used (Boustead and Hancock, (1979), and from the current mix of electrical power generation stations (DTI, 1995 and Gover et al, 1996) for the emissions, plus an allowance for the compression or liquefaction of gaseous hydrogen, as detailed in section 7.3.8 below.

7.3.2 PETROL AND DIESEL

Petrol and diesel fuels are produced from crude petroleum oil and involves the following processes:

(a) drilling to extract the crude oil from the Earth's crust,

(b) separation of the crude oil from natural gas liquids,

(c) transport to oil refineries,

(d) processing to produce petrol and diesel fuels,

(e) distribution to terminals and filling stations,

(f) dispensing to user.

The overall energy used in, and the emissions from, these processes, plus those for losses due to distribution and dispensing, are shown in Tables 7.1 and 7.2 (Gover et al, 1996). Less energy is used in the manufacture of diesel than petroleum, with most in each case being split between extraction and refining. This split is approximately 50/50 for diesel and 40/60 (extraction/refining) for petroleum. Emissions follow the same overall trend, but the split between the various operations can vary considerably. For instance, transport has a larger share than extraction because of emissions from the vehicles involved. The relatively large figure for NMVOCs from the distribution of petroleum is due to evaporative emission at terminals and service stations.

TABLE 7.1 PETROLEUM

	Energy MJ/GJ	CO2 kg/GJ	CO g/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ
Extraction	62.4	3.4	1.5	9.5	10.9	0.0	14.7	0.0
Transport	8.2	0.6	1.7	16.0	25.8	11.2	0.3	0.0
Refining	96.3	6.1	1.4	13.4	67.7	57.0	0.2	0.0
Distribtn.	2.0	0.2	0.4	1.6	107.5	1.1	0.4	0.1
TOTAL	168.6	10.3	5.0	40.5	211.8	69.3	15.6	0.1

TABLE 7.2 DIESEL FUEL

	Energy MJ/GJ	CO2 kg/GJ	CO g/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ
Extraction	58.7	3.2	1.4	9.0	10.6	0.0	13.8	0.0
Transport	7.7	0.6	1.6	15.0	24.2	10.5	0.2	0.0
Refining	53.4	3.0	0.8	6.5	56.8	34.0	0.1	0.0
Distribution	1.9	0.2	0.4	1.5	0.3	1.1	0.4	0.1
TOTAL	121.7	6.9	4.2	32.0	91.6	45.6	14.6	0.1

7.3.3 PROPANE

In the UK, Liquid Petroleum Gas (LPG) consists of 90% propane (Poulton, 1993) with other hydrocarbons such as butanes (C_4H_{10}), propylene (C_3H_6) and butylene (C_4H_8), (Gover et al, 1996). The gases are liquefied by the application of a relatively low pressure or refrigeration. As for petrol and diesel, LPG is produced from crude oil and in addition to extraction, separation, and the transport to refineries, involves the following:

(a) fractionation of natural gas liquids,

(b) transport of LPG,

(c) refrigerated storage,

(d) distribution to filling stations,

(e) dispensing to user.

The overall energy used in, and the emissions from, these processes, plus those for

losses, are shown in Table 7.3 (Gover et al, 1996). The overall energy used in the production of LPG is about the same as for diesel, but mainly split about 65/35 between extraction and refining. The emissions are comparable with those for diesel, except for NMVOCs, which is noticeably less.

TABLE 7.3 (LPG)

	Energy MJ/GJ	CO2 kg/GJ	CO g/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ
Extraction	64.7	3.5	1.6	9.8	11.7	0.0	16.2	0.0
Transport	8.6	0.6	1.8	17.8	14.1	11.9	0.1	0.0
Refining	35.8	2.7	0.5	5.8	38.2	25.4	0.1	0.0
Storage	7.5	0.4	0.1	1.2	0.0	3.6	0.5	0.0
Distribution	5.6	0.4	1.7	5.7	0.2	0.1	0.0	0.5
TOTAL	122.2	7.6	5.8	39.5	64.2	41.0	17.0	0.5

7.3.4 NATURAL GAS

In the UK, natural gas from the North Sea consists of the following mixture of gases:

(a) methane (CH_4) 93.63%,

(b) ethane (C_2H_6) 3.25%,

(c) nitrogen 1.78%0,

(d) propane (C_3H_8) 0.69%

(e) butane (C_4H_{10}) 0.27%,

(f) other hydrocarbons 0.2%,

(g) carbon dioxide 0.13%,

(h) helium 0.05%.

Natural gas is produced using the following processes:

(a) drilling to extract the crude gas from the Earth's crust,

(b) processing at the drilling site to separate the natural gas,

(c) transport to storage and filling stations,

(d) compression and delivery to user.

The overall energy used in, and the emissions from, these processes, plus those for losses due to processing, distribution, leakage and compression, are shown in Table 7.4 (Gover et al, 1996). For natural gas, the energy used in manufacture is about half that for diesel and LPG, with about half the total due to extraction. Two thirds of the remaining half is attributable to filling station operations, where energy is used to compress the gas for delivery to vehicles. For this reason the energy and emissions at filling stations are relatively high compared with liquid fuels.

TABLE 7.4 NATURAL GAS

	Energy	CO2	CO	NOx	NMVOC	SO2	CH4
	MJ/GJ	kg/GJ	g/GJ	g/GJ	g/GJ	g/GJ	g/GJ
Extraction	30.9	1.6	1.0	4.1	11.0	1.1	20.0
Distribution	10.0	0.0	0.0	0.0	16.0	0.0	198.8
Filling Stn	20.0	3.2	0.9	10.1	9.7	27.1	0.0
TOTAL	60.9	4.8	1.9	14.2	36.7	28.2	218.8

7.3.5 METHANOL

Two different routes are considered for the production of methanol, firstly by current industrial methods and secondly by the conversion of a suitable biomass to produce biomethanol.

Currently, more than 85% of methanol is produced from natural gas (Johansson et al, 1993) by processing to remove other hydrocarbons and sulphur, and then steam reforming to produce carbon monoxide and hydrogen, as already described in chapter 5:

$$CH_4 + H_2O \text{ ---> } CO + 3H_2 \qquad [11]$$

$$\text{and } CO + H_2O \text{ ---> } CO_2 + H_2 \qquad [12]$$

resulting in:

$$CH_4 + 2H_2O \text{ ---> } CO_2 + 4H_2 \qquad [13]$$

Methanol is then synthesised by catalytically reacting carbon dioxide and hydrogen to give methanol and water:

$$CO_2 + 3H_2 \text{ ---> } CH_3OH + H_2O \qquad [14]$$

Because of the above two energy absorbing processes for producing hydrogen from natural gas followed by the production of methane from hydrogen, the use of reformed methanol as a fuel may not be worthwhile unless the use of a fuel which is liquid at normal temperature and pressure is required. Otherwise, if a compressed gas is acceptable as a fuel for inboard reforming, then the use of natural gas would be a better option.

That part of the overall energy and carbon dioxide emissions for the production of methanol from natural gas are calculated assuming that 10% to 15% of the gas is used to provide the heat and steam for the endothermic reforming process (BP, 1972 and 1989, DeLuchi et al, 1993 and Dicks, 1995). From the chemical equations for the reforming process, equation [13] above, and using gramme molecular weights, the ratio of methane/hydrogen is 16.042/8.064. From the chemical equation for the combustion of natural gas:

$$CH_4 + 2O_2 \text{ ---> } CO_2 + 2H_2O \quad [15]$$

the ratio of carbon dioxide/methane is 44.01/16.042 and, from equation [14] above, the ratio of methanol/hydrogen is 32.042/6.048. Thus, assuming a mean value of 12.5% for the amount of additional natural gas used to provide the heat of reformation, the ratio of carbon dioxide/methanol is:

$$0.125*(16.042/8.064)*(44.01/16.042)*(6.048/32.042) = 0.1289 \text{ kg}CO_2/\text{kg}CH_3OH \quad [16]$$

This is about 25% less than that from published estimates for the emissions from industrial plant for the production of methanol using the above processes, as given in Table 7.5 (ETSU, 1994a).

TABLE 7.5 METHANOL (from Natural Gas)

	CO2 kg/GJ	CO g/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ
Industrial Plant Emissions	7.0	4.0	11.0			2.0

Additional emissions occur from the production of natural gas used, as already detailed in Table 7.4.

The additional 25% is considered to be due to other processes in the plant such as preheating prior to hydrodesulphurization, pumping of fluids and removal of water by

distillation of the methanol/water product.

Biomethanol produced from wood has been extensively studied and reported eg (DeLuchi, 1991, Johansson et al 1993 and Gover et al, 1996). The main processes in the production of methanol from wood are:

(a) agriculture to produce wood crop,

(b) harvesting and transport to processing plant,

(c) processing wood to methanol, which includes gasification, gas reforming similar to that for industrial methanol, above, cooling and compression of the hydrogen mixture, synthesis to methanol and final distillation,

(d) distribution to storage and filling stations, including evaporative emissions of NMVOC due to loading and breathing losses at main terminals, tankers and service stations, and vehicle refuelling losses.

The energy used in, and the emissions from, these processes, plus those for losses, are shown in Table 7.6 based on (Gover et al, 1996).

TABLE 7.6 BIOMETHANOL (from Wood)

	Energy MJ/GJ	CO2 kg/GJ	CO g/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ
Agriculture	44	1.655	8.8	21.8	4.0	0.4		3.3
Processing (Assumes use of natural gas and electric power from current power stations to provide energy for processing (Gover et al, 1966)).	433	22.694	2.6	28.4	174.2	22.3		0.5
Transport	27	1.942	8.9	29.7	1.0	0.6		2.4
Distribution	1	0.764	3.5	11.7	22.1	0.3		1.0
TOTAL	514	27.055	23.8	91.6	201.3	23.7		7.2

The energy used in the manufacture fuels from a crop is significantly higher than for fossil fuels, and is due mainly to processing operations. For biomethanol, the processing energy is over 80% of the total, and accounts for the high emissions due to the processing operation.

7.3.6 ETHANOL

Ethanol can be produced from fossil fuels such as natural gas and oil, and is termed bioethanol when produced from the fermentation of carbohydrates in biomass such as sugar and starch crops. Bioethanol is produced from sugar crops in Brazil as an alternative fuel for road transport (Johansson et al, (1993). The main processes in the production of bioethanol from a crop are:

(a) agriculture and production of crop,

(b) harvesting and transport to processing plant,

(c) processing and fermentation to produce ethanol,

(d) distillation and dehydration,

(e) distribution to storage and filling stations, including evaporative emissions of NMVOC due to loading and breathing losses at main terminals, tankers and service stations, and vehicle refuelling losses.

The overall energy used in, and emissions from, these processes for the production of bioethanol from wheat are shown in Table 7.7 (Gover et al, 1996).
The overall energy is about the same as that for biomethanol, but mainly split 50/50 between agriculture and processing. Emissions are highest during the processing operations, but amounts for different pollutants differ from those for biomethanol.

This is because the operations and energy sources are significantly different.

TABLE 7.7 BIOETHANOL
(From wheat using byproduct straw burning for processing)

	Energy MJ/GJ	CO2 kg/GJ	CO g/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ
Agriculture	271	6.126	27.4	68.0	12.5	1.4		10.3
Processing (Assumes use of straw as fuel to produce energy for steam generation (Gover et al, 1996)).	212	12.563	78.0	86.4	86.2	157.1		16.7
Transport	19	1.322	6.1	20.3	0.7	0.5		1.6
Distribution	8	0.561	2.6	8.6	10.4	0.2		0.7
TOTAL	510	20.572	114.1	183.3	109.8	159.2		29.3

7.3.7 RAPE METHYL ESTER (RME)

Methyl esters are produced from vegetable oils produced from crops such as palm, rape seed, sunflower seed and soybeans. In Europe, one of the main oil seed crops grown is rape seed, which can be used as an alternative to diesel fuel when it is known as biodiesel. The main processes in the production of RME from rape seed are:

(a) agriculture and production of crop,

(c) crushing and extraction of rape seed oil,

(d) esterification to produce RME by catalytically reacting the acidic oil with methanol,

(e) distribution to storage and filling stations, including evaporative losses as for biomethanol and bioethanol, above.

The overall energy used in, and the emissions from, these processes are shown in Table 7.8 (Gover et al, 1996).

TABLE 7.8 RAPE METHYL ESTER (RME)
(From average of winter and summer rape seed oil crops)

	Energy MJ/GJ	CO2 kg/GJ	CO g/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ
Agriculture plus oil extraction (Assumes use of straw as fuel to produce energy for oil extraction process (Gover et al, 1996)).	554	19.144	49.3	149.2	60.05	111.4		19.7
Processing	89		35.6	19.0	16.6	5.9		6.4
Transport	12	0.830	3.9	12.7	0.5	0.2		1.1
Distribution	5	0.357	1.6	5.5	0.2	0.1		0.5
TOTAL	660	20.331	90.4	186.4	77.4	117.7		27.7

The energy and consequent emissions shown due the agriculture etc of rapeseed is higher than the other biofuels because it includes that for oil extraction. Overall, the figures are comparable with those for bioethanol.

7.3.8 HYDROGEN

The energy used in, and emissions produced from, the production of hydrogen by electrolysis using the current mix of electrical power generating stations are calculated using published data for the amount of energy used (Boustead and Hancock, 1979) as given in Table 7.9, the emissions produced from power stations as given in Tables 7.10 to 7.12 and data for the current mix of electric power stations, (Gover et al, 1996) as given in Table 7.13, resulting in the emissions shown in Table 7.14.

TABLE 7.9 PRODUCTION ENERGY FOR HYDROGEN
(Energy requirements in MJ/kg for hydrogen from electrolysis of brine apportioned over hydrogen/chlorine outputs on a mass basis)

Production	Energy Content of Fuels Used	TOTAL
0.25	7.64	9.59

TABLE 7.10 EMISSIONS FROM COAL FIRED POWER STATIONS (1995)

	CO2 kg/GJ	CO g/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ	N20 g/GJ
Generation	269.1	37.1	776.0	5.1	2359	1.7	47.0	14.3
Transport	0.3	2.5	5.9	1.7	0.1	0.4	9.3	0.0
Processing, Extraction	0.4	0.8	1.7	0.4	0.0	1004	0.0	0.0
TOTAL	269.8	40.5	783.6	7.2	2359	1006	56.3	14.3

TABLE 7.11 EMISSIONS FROM OIL FIRED POWER STATIONS (1995)

	CO2 kg/GJ	CO g/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ	N20 g/GJ
Generation	238.5	46.1	623.3	7.2	3252	1.8	119.7	51.5
Transport				6.3		0.5		
Processing	18.2	5.8	28.8	28.8		0.5		1.9
Extraction	6.9	6.9	19.6	1.0		9.8		1.0
TOTAL	263.6	58.7	671.7	43.3	3252	12.5	119.7	54.4

TABLE 7.12 EMISSIONS FROM NUCLEAR POWER STATIONS (1995)

	CO2 MJ/GJ	CO kg/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ	N2O g/GJ
Extraction	0.3		1.9			9.4		
Processing	0.9		5.6			5.6		
TOTALS	1.3		7.5			15.0		

TABLE 7.13 CURRENT MIX OF ELECTRIC POWER STATIONS (1995)

	Coal	Oil	Gas	Nuclear	Hydro
Average Mix	45.0%	6%	20.0%	27.0%	2.0%
Night Mix	41.7%	0	23.8%	32.1%	2.4%

TABLE 7.14 EMISSIONS FROM ELECTRICITY USE
(From average mix of power stations in 1995)

	CO2 MJ/GJ	CO kg/GJ	NOx g/GJ	NMVOC g/GJ	SO2 g/GJ	CH4 g/GJ	PM g/GJ	N2O g/GJ
Average	161.8	45.3	443	8.2	1356	479.2	32.5	10.1
Night	141.7	45.0	386.1	5.6	1079	449.9	23.2	6.4

The amount of carbon dioxide produced as the result of the production of hydrogen by electrolysis using various dedicated renewable energy sources are calculated using published data (LaPorta, 1990) as given in Table 7.15.

TABLE 7.15 CO_2 EMISSIONS FROM RENEWABLE POWER PLANTS
(In Tonnes CO_2/GWh output for plant construction)

Technology	Construction	Operation	TOTAL
Geothermal Steam	1.0	55.8	56.8
Wind Energy	7.4		7.4
Photovoltaics	5.4		5.4
Large Hydro-electric	3.1		3.1

7.4 ENERGY AND EMISSIONS FROM FUEL USAGE AND TOTALS INCLUDING PRODUCTION

7.4.1 ENERGY

The assessment of impacts in terms of energy requirements from usage of fuel depend upon the system. For the internal combustion engine and fuel cell, fuel consumption and higher heating values are used to calculate energies.

Energies used in production are calculated (in terms of MJ of energy per kWh of energy developed by a vehicle power source) from the values of fuel consumption (kg of fuel per kWh) calculated above and given in Table A.1, and the values (of MJ of energy used in production per GJ of fuel) in Tables 7.1 to 7.8 and the higher heating values (in GJ energy per kg of fuel) as follows:

Production Energy/kWh = (kg of Fuel/kWh)*(MJ of Production Energy/GJ of Fuel)*(GJ/kg of Fuel) [17].

Values for the production of hydrogen by electrolysis are calculated using Table 7.9.

Energies used during fuel usage (in terms of MJ of energy /kWh of energy developed by a vehicle power source) are calculated from the calculated values of fuel consumption (kg of fuel per kWh) and the higher heating values (in MJ of energy per kg of fuel) as follows:

Used Energy/kWh = (kg of Fuel/kWh)*(MJ of Used Energy/kg of Fuel) [18].

Table A.2 in Appendix A gives the energy consumptions calculated as above, for the production and usage of the various fuels considered, plus the totals for each fuel. In the table, fuel consumption is included and methanol refers to methanol produced from natural gas and biomethanol from crops.

These results are plotted against efficiency in Figures 7.4 to 7.7.

Figure 7.4 Total Energy Consumptions for Fuel Cells

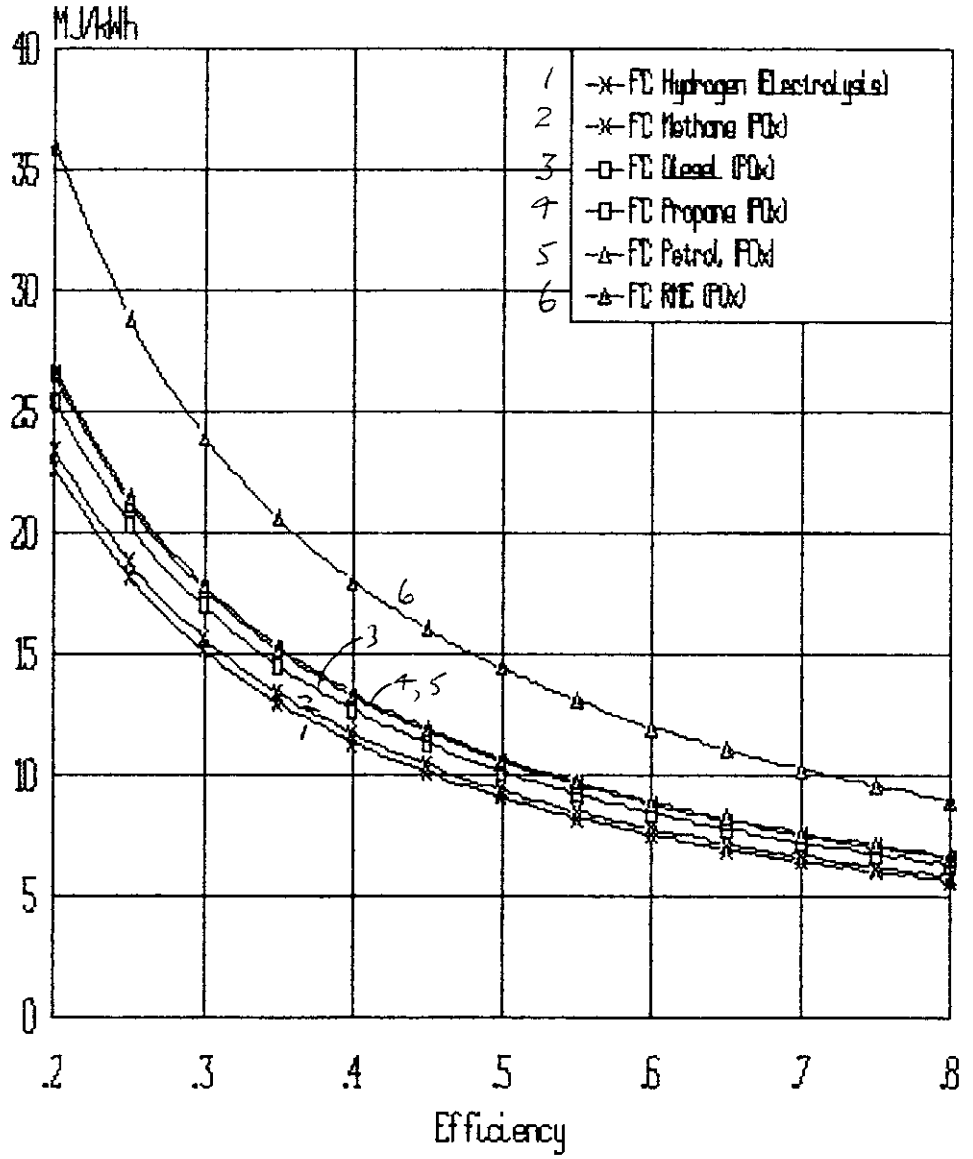


Figure 7.5 Total Energy Consumptions for Fuel Cells

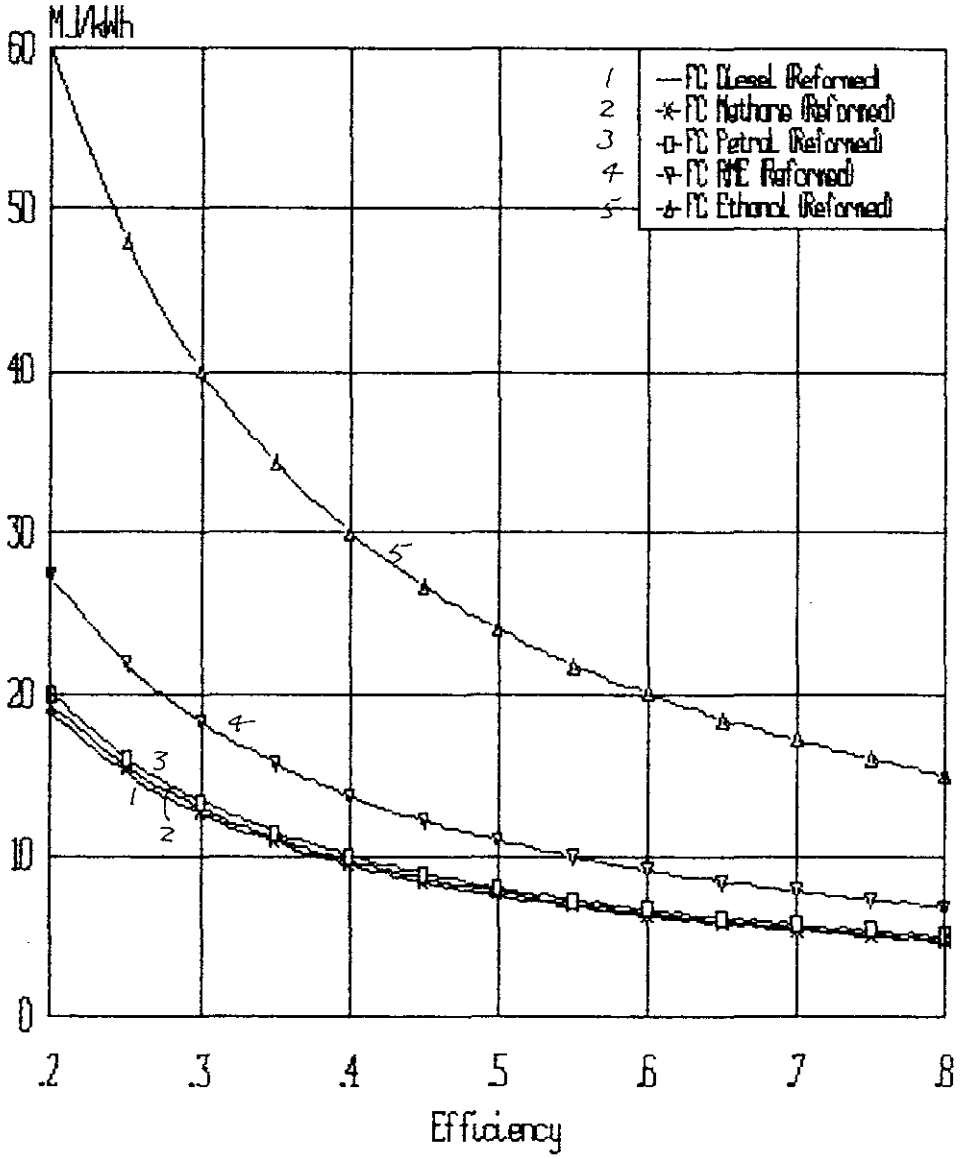


Figure 7.6 Total Energy Consumption for Fuel Cells

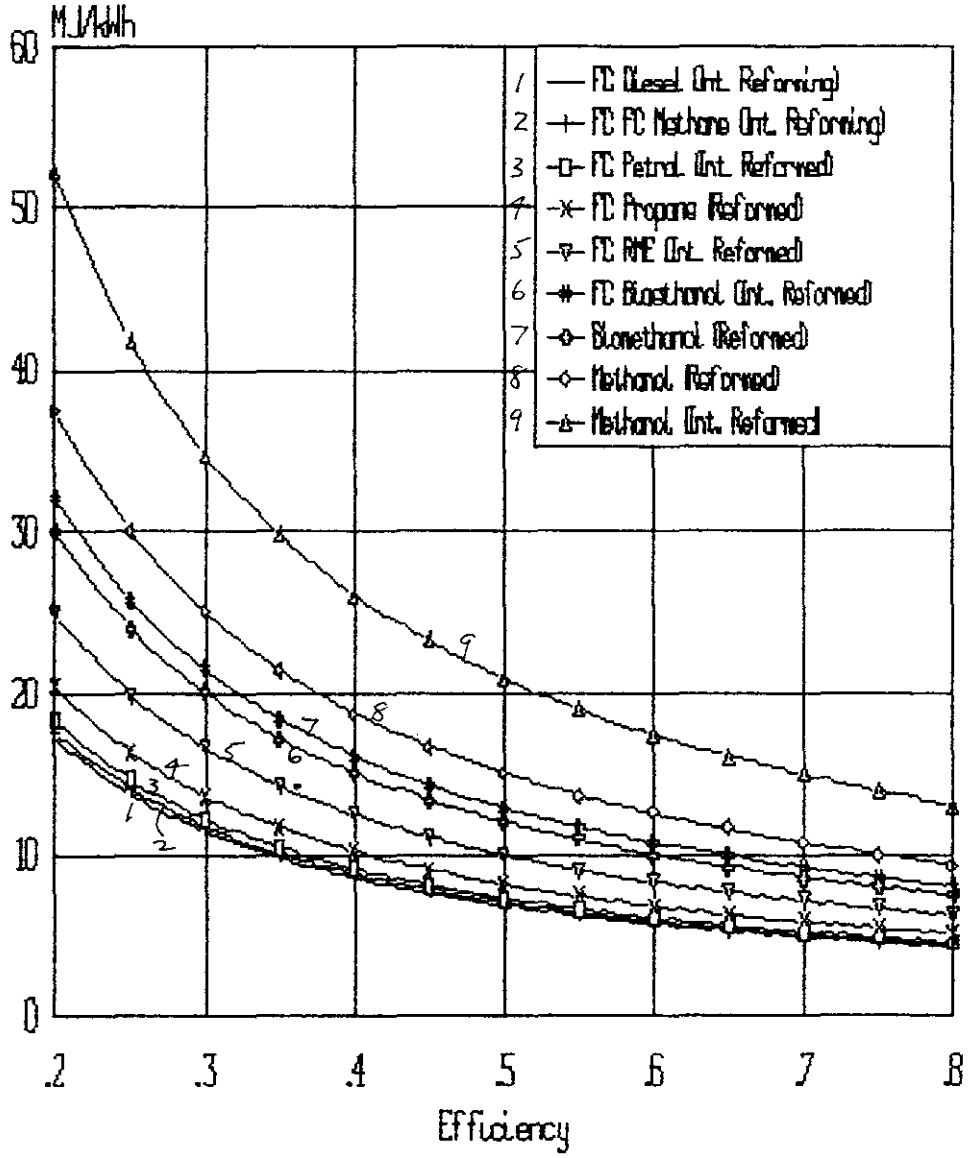
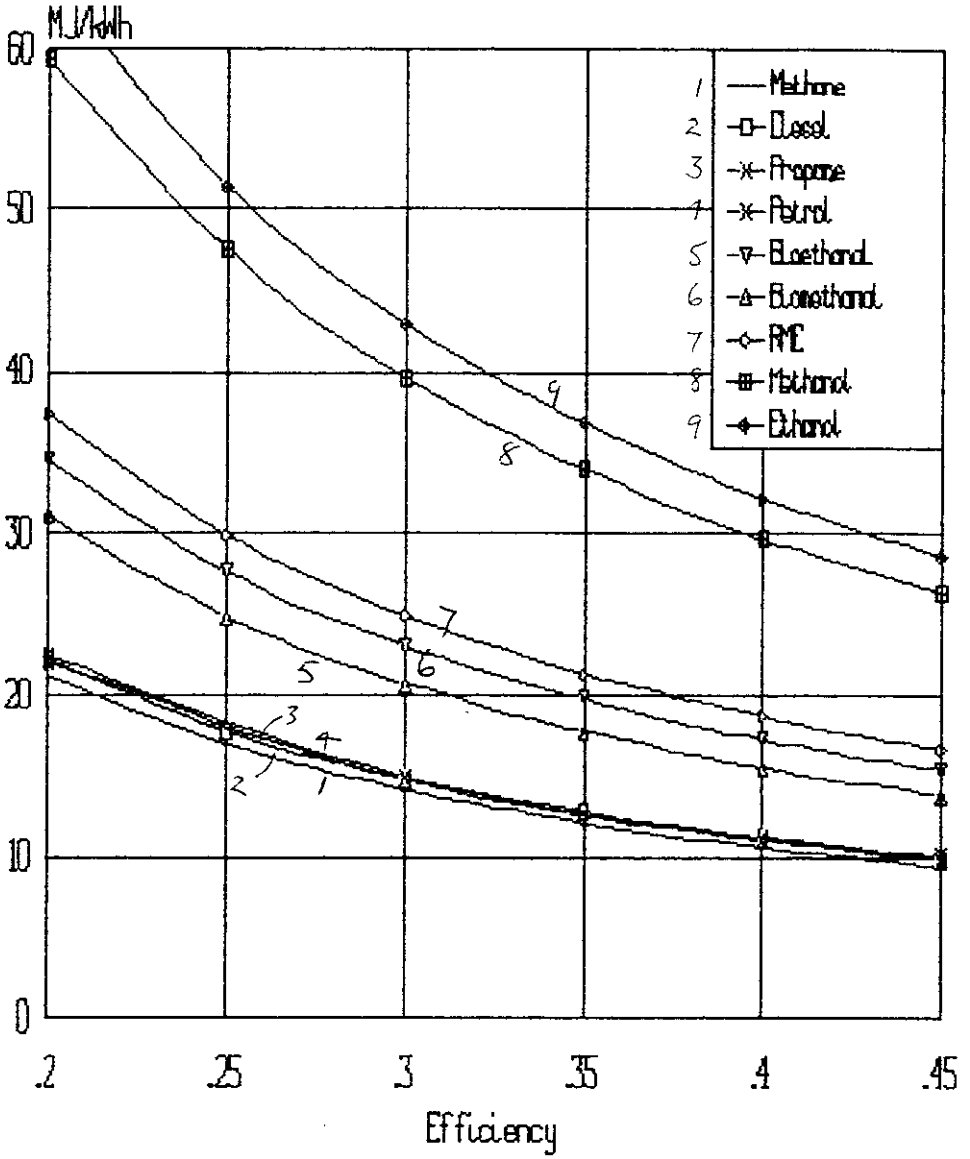


Figure 7.7 Total Energy Consumption for ICEs



7.4.2 EMISSIONS

The emissions from the manufacturing processes (in terms of mass of pollutant per kWh of energy developed by a vehicle power system) are calculated for the various fuels using the values for fuel consumption (kg of fuel/kWh) in Table A.1 Appendix A, the mass of pollutant/GJ of fuel energy given in section 7.3 above and the fuel higher heating values in GJ/kg:

Mass of Pollutant/kWh = (Mass of Pollutant/GJ)
(GJ/kg of Fuel)(kg of Fuel/kWh) [19].

Emissions during usage for the various fuels considered are calculated from published data (IPCC, 1995) for IC engines and calculated using the equations for the chemical reactions for the various reformed fuels in fuel cells.

7.4.2.1 IC ENGINES

For IC engines, the amounts of pollutants for a range of efficiency (0.2 to 0.45) are calculated using published data (IPCC,1995), Table 7.16 below, selected for engines with advanced exhaust control and suitable for public transport, and the fuel consumption calculated in section 7.2.4, above.

As a check, the amount of carbon dioxide is calculated using the chemical equations for the complete combustion saturated hydrocarbon fuels:

$$2C_nH_{(2n+2)} + (3n+1)O_2 \quad ---> \quad 2nCO_2 + (2n+2)H_2O \qquad [20].$$

Thus for:

(a) the assumed chemical formula for petrol,

$$\text{kg } CO_2/\text{kg } C_7H_{16} = 308.07/100.198 = 3.0746 \quad [21]$$

(b) the assumed chemical formula for diesel fuel,

$$\text{kg } CO_2/\text{kg}C_{16}H_{34} = 704.16/226.432 = 3.1098 \quad [22]$$

(c) liquid petroleum gas, mainly propane,

$$\text{kg } CO_2/\text{kg } C_3H_8 = 132.03/44.094 = 2.9943 \quad [23]$$

(d) natural gas, mainly methane,

$$\text{kg } CO_2/\text{kg } CH_4 = 44.01/16.042 = 2.7434 \quad [24].$$

For methanol, the combustion equation is,

$$2CH_3OH + 3O_2 \text{ ---> } 2CO_2 + 4H_2O \quad [25]$$

giving,

$$\text{kg } CO_2/\text{kg } CH_3OH = 88.02/64.084 = 1.3735 \quad [26].$$

The above calculated values are found to compare well with the published estimates for greenhouse gas emissions from internal combustion engines using petrol, diesel, natural gas, LPG and methanol, given in Table 7.16 (IPCC, 1995). Thus, this gives sufficient confidence to calculate the CO_2 figures for ethanol and RME using chemical equations for combustion.

For ethanol, the combustion equation is,

$$C_2H_5OH + 3O_2 \text{ ---> } 2CO_2 + 3H_2O \quad [27]$$

giving,

$$\text{kg } CO_2/\text{kg } C_2H_5OH = 88.02/46.068 = 1.9107 \quad [28].$$

For RME, the combustion equation is,

$$2C_{19}H_{38}O_2 + 57O_2 \text{ ---> } 38CO_2 + 38H_2O \quad [29]$$

giving,

$$\text{kg } CO_2/\text{kg RME} = 1672.38/596.99 = 2.8014 \quad [30]$$

The other pollutants for ethanol and RME and the values for the emission of particulate matter from IC engines in Table 7.16 are only given in terms of g/km in published data, and values for gPM/kg of fuel have been calculated using the published driving cycles and fuel consumptions for urban buses (Gover et al, 1996).

TABLE 7.16 EMISSIONS FROM IC ENGINES (g/kg of fuel)
(Public Transport size and advanced exhaust control)

	CO2	CO	NOx	NMVOC	CH4	N2O	PM
			(g/kg of fuel)				
Petroleum	3014.5	44.59	8.03	5.98	0.312	0.78	0.7
Diesel Fuel	3188	22.09	16.27	4.09	0.19	0.08	2.7
Natural Gas	2750	5.0	13.3	1.3	13.3		0.41
LPG	3000	4.3	11.2	3.0	0.6		0.67
Methanol	1375[1]	6.1	6.1	2.3	0.01		0.51
Ethanol	1913[1]	23.64	14.64	6.23[2]			0.51
RME	2815[1]	14.83	18.72	3.4[2]			1.84

[1]For biofuels, such as bioethanol, biomethanol and RME derived from cop processing, the carbon dioxide during engine usage can be offset over a long time scale by the carbon dioxide absorbed during crop growth.

[2]NMVOC plus Methane.

7.4.2.2 FUEL CELLS USING REFORMED FUELS

For fuel cell systems using reformed fuels, the amounts of carbon dioxide for a range of efficiency (0.2 to 0.8) are calculated using the chemical equations for the reforming reactions and the fuel consumption, both given in sections 7.2.1 and 7.2.2, above. From equation [4] in section 7.2.2, above, and allowing for the additional 10% of fuel to provide the heat of reformation for external reforming, the amounts of carbon dioxide **from the reforming reaction** for saturated hydrocarbon fuels (C_nH_{2n+2}) are calculated using gramme molecular weights:

$$\text{kg } CO_2/\text{kg } (C_nH_{2n+2}) = 44.01n/(14.026n+2.016) \quad [31]$$

Because complete oxidation is assumed to take place, this gives the same value as given in section 7.4.2.1, above, for the combustion of saturated hydrocarbons. The amounts of additional CO_2 and other pollutants produced from the external reformer by burning the additional 10% of fuel are calculated below, after the next two paragraph on calculations for RME and alcohols.

For RME, assuming the chemical formula and reforming reaction assumed in chapter 5 and equation [6] in section 7.2.2:

$$C_{19}H_{38}O_2 + 36H_2O \text{ ----> } 55H_2 + 19CO_2 \quad [32]$$

the amount of carbon dioxide **from the reforming reaction** are calculated using gramme molecular weights:

$$\text{kg } CO_2/\text{kg } (C_{19}H_{38}O_2)_{ir} = 836.19/298.49 = 2.8014 \quad [33]$$

For ethanol and methanol the amount of carbon dioxide **from the reforming reaction** is calculated from the chemical reforming equations, [7] and [8] in section 7.2.2:

For ethanol:

$$C_2H_5OH + 3H_2O \text{ ---> } 2CO_2 + 6H_2 \quad [34]$$

giving,

$$\text{kg } CO_2/\text{kg } (C_2H_5OH)_{ir} = 88.02/46.068 = 1.9106 \quad [35]$$

For methanol:

$$CH_3OH + H_2O \text{ ----> } CO_2 + 3H_2 \quad [36]$$

giving,

$$\text{kg } CO_2/\text{kg } (CH_3OH)_{ir} = 44.01/32.042 = 1.3735 \quad [37]$$

For biofuels, such as RME, bioethanol and biomethanol which are all derived from crops, the amount of carbon dioxide produced during fuel usage can, in the long term, be offset by that absorbed from the atmosphere during crop growth. However, the calculations are made and results given to indicate the amounts of pollutant that are emitted from vehicles.

The amounts of additional CO_2 and other pollutants from external reformer systems are mainly due to the additional amount of fuel (10%) burnt to provide heat for the reformer. In a practical system these additional pollutants, other than the CO_2, probably could be removed by advanced exhaust control. Estimates for these additional pollutants are calculated from published data (IPCC, 1995) for the quantities of fuel required to be burnt to produce the heat and steam for the endothermic reforming reaction. These quantities of fuel are from published data; Virji et al (1995) and Hohlein et al (1996) for methanol reformers, and BP (1972, 1989) and Dicks (1995) for hydrocarbon fuels.

For fuel cells using externally reformed fuels, the total amounts of CO_2 during usage (in terms of kg of CO_2 per kWh of energy developed by a power system) are

calculated from the values of fuel consumption from section 7.2, above, the ratios of kg of CO_2/kg of fuel, above, and the amounts of CO_2 from the of 10% additional fuel used to provide the heat of reformation (in terms of kg of pollutant per kg of fuel).

Thus, for saturated hydrocarbons:

$$\text{kg } CO_2/\text{kWh} = [\{\text{kg Reformed Fuel/kWh}\}*\{44.01n/(14.026n+2.016)\}/1.1] + [(\text{kg } CO_2/\text{kg Burnt Fuel})*(\text{kg Reformed Fuel/kWh})/11] \quad [38]$$

for external reforming and, for internal reforming this becomes:

$$\text{kg } CO_2/\text{kWh} = \{\text{kg Reformed Fuel/kWh}\}*\{44.01n/(14.026n+2.016)\} \quad [39]$$

For RME, the calculations are:

$$\text{kg } CO_2/\text{kWh} = [(\text{kg Reformed RME/kWh})*(836.19/298.49)/1.1] + [(\text{kg } CO_2/\text{kg Burnt RME})*(\text{kg Reformed RME/kWh})/11] \quad [40]$$

for external reforming or,

$$\text{kg } CO_2/\text{kWh} = (\text{kg RME/kWh})*(836.19/298.49) \quad [41]$$

for internal reforming.

For methanol, the calculations are:

$$\text{kg } CO_2/\text{kWh} = [(\text{kg Reformed } CH_3OH/\text{kWh})*(88.02/64.08)/1.1] + [(\text{kg } CO_2/\text{kg Burnt } CH_3OH)*(\text{kg Reformed } CH_3OH/\text{kWh})/11] \quad [42]$$

for external reforming or,

$$\text{kg } CO_2/\text{kWh} = (\text{kg Reformed } CH_3OH/\text{kWh})*(88.02/64.08) \quad [43]$$

for internal reforming.

For ethanol, these calculations are:

$$\text{kg } CO_2/\text{kWh} = [(\text{kg Reformed } C_2H_5OH/\text{kWh})*(88.02/46.068)/1.1] + [(\text{kg } CO_2/\text{kg Burnt } C_2H_5OH)*(\text{kg Reformed } C_2H_5OH/\text{kWh})/11] \quad [44]$$

for external reforming or,

$$\text{kg } CO_2/\text{kWh} = (\text{kg Reformed } C_2H_5OH/\text{kWh})*(88.02/46.068) \quad [45]$$

for internal reforming.

For external reforming, other pollutants (carbon monoxide, methane, non methane volatile hydrocarbons nitrogen oxides and PM) are produced from the additional fuel used to provide the heat of reformation. The amounts of these pollutants (per kWh of energy developed by a power system), which could be reduced by effective treatment of the flue gases from the reformer, are calculated using values of fuel consumption for the various fuels, taking into account the 10% additional fuel:

$$\text{Mass Pollutant/kWh} = (\text{Mass Pollutant/Unit Mass Burnt Fuel}) *(\text{Mass Reformed Fuel/kWh})/11 \quad [46].$$

7.4.2.3 FUEL CELLS USING PARTIAL OXIDATION OF FUELS

For fuel cell systems using the partial oxidation of fuels followed by a carbon monoxide shift reaction, the main pollutant is carbon dioxide. Emissions of CO_2 are calculated using the chemical equations for the partial oxidation of the various fuels.

For saturated hydrocarbons, equation [9] from section 7.2.3 above, gives:

$$2C_nH_{(2n+2)} + nO_2 + 2nH_2O \text{ ---> } (4n+2)H_2 + 2nCO_2 \quad [47]$$

and substituting gramme molecular weights, the ratio of CO_2 emitted to hydrogen produced is 88.04n/(8.0648n+4.032).

For RME, equation [10] from section 7.2.3 above, gives:

$$2C_{19}H_{38}O_2 + 17O_2 + 38H_2O = 76H_2 + 38CO_2 \quad [48]$$

and substituting gramme molecular weights, the ratio of CO_2 emitted to hydrogen produced is 1672.38/153.22 = 10.91.

Thus, the amounts of CO_2 (in terms of kg CO_2 per energy developed by a fuel cell power system) are calculated using the fuel cell hydrogen fuel consumption and the ratio of CO_2 emitted to hydrogen produced for the various fuels:

$$\text{kg } CO_2/\text{kWh} = (\text{kg } CO_2/\text{kg } H_2)*(\text{kg } H_2/\text{kWh}) \quad [49].$$

7.4.2.4 FUEL CELLS USING HYDROGEN

For fuel cell systems using hydrogen the waste product is water and the pollutants are from the hydrogen manufacturing processes, plus an allowance for energy used for the liquefaction or compression of gaseous hydrogen.

The pollutants (in terms of mass of pollutant per kWh of energy developed by a vehicle power system) produced from the manufacture of hydrogen by electrolysis using the current mix of electrical power generating stations are calculated from the mass of pollutant per GJ of energy generated (Table 7.14), the amount of energy required to produce unit mass of hydrogen by electrolysis (Table 7.9) and the hydrogen consumption (Table A.1 in Appendix A).

Mass of Pollutant/kWh = (Mass of Pollutant/GJ)

(GJ/Unit Mass of H_2 Produced)(Mass of H_2/kWh) [50]

The pollutants (in terms of mass/kWh of power developed by a power system) produced from the manufacture of hydrogen by electrolysis using nuclear power stations are calculated in the same way but using Tables 7.9 and 7.12 above, and Table A.1 in Appendix A.

Carbon dioxide (in terms of mass/kWh of power developed by a power system) produced from the manufacture of hydrogen by electrolysis using renewable resources are calculated from the data in Tables 7.9 and 7.15 above, and Table A.1 in Appendix A.

7.4.2.5 RECHARGING BATTERIES

Emissions for battery driven vehicles are produced from electrical power generating stations during the recharging phase. These are calculated for a range of battery efficiency (0.6 to 0.85), in terms of mass of pollutant per kWh of energy developed by a battery system, using the emissions from the current mix of power stations (Table 7.14) assuming a battery charger efficiency of 0.9:

Mass Pollutant/kWh = (Mass Pollutant/GJ Fuel)

*3600/0.9/Battery efficiency [51].

7.4.3 RESULTS OF EMISSION CALCULATIONS

Tables A.3 to A.10 in Appendix A give the amounts of pollutants for the various fuels emitted during usage and the totals, including manufacture, in terms of kg or g of pollutant/kWh of power developed by a vehicle power system.

7.5 DISCUSSION OF RESULTS

7.5.1 INTRODUCTION

In all cases, most carbon dioxide emission is from the use of fuels, and in the case of fuel cells, the other emissions are mainly due to fuel manufacture. For fuel cells with their increased efficiency and hence reduced fuel consumption, emissions are reduced, in some cases significantly, when compared with IC engines.

The results for externally reformed fuels, referred to as "reformed" in Tables A.3 to A.10 in Appendix A assume that the flue gases from the reformer burner are not cleaned or oxidised. **These flue gases could be reduced to negligible quantities by an advanced control system, making them, apart from the carbon dioxide, essentially the same as for internally reformed fuels.**

For biofuels, the results for carbon dioxide can, in the long term, be reduced to that portion emitted during fuel production if the amount emitted during fuel usage if offset by the amount absorbed during the biocrop growing period. The results are calculated so as to show the emissions during the periods of fuel production, usage and their total, and the amounts of CO_2 that could be offset are expressed as percentages in the appropriate sections, below. However, the advantage of reducing CO_2 emissions this way has to be balanced against the increases in other emissions (CO, NOx and SO_2) from the manufacture of biofuels and the areas of land needed to be dedicated for crop growing.

Results for fuel cells have been calculated for efficiencies from 0.2 to 0.8 and those for IC engines from 0.2 to 0.45. Although confirmation of up to date data on the fuel consumptions and efficiency of fuel cells could not be obtained, it is expected that fuel cells for practical systems will have efficiencies between 0.45 and 0.65 depending upon

the type. IC engines could be expected to have efficiencies between 0.25 and 0.35. Thus, comparison will be confined to the above ranges; numerical values quoted in the following sections are for these efficiency ranges.

The results for recharging battery driven vehicles have been calculated assuming emissions for the current mix of electric power generation stations during both the overnight period and a 24 hour average. In practice, if a large number of vehicles are put on charge overnight this might entail a change in the mix of power stations.

The discussion describes and compares the results for each pollutant in sections 7.5.2 to 7.5.8. The results are then considered in section 7.6 in broader terms in the context of further work in later chapters on through life emissions and methods of introducing fuel cell technology to the transport sector.

7.5.2 CARBON DIOXIDE

Carbon dioxide emitted from the combustion of fossil fuels in IC engines is one of the major sources of global warming, see Chapter 1. An overall reduction in carbon dioxide emissions by the year 2020 to 80% of the 1990 level is a declared target, (Chapter 1).

7.5.2.1 FUEL CELLS (CO_2)

For fuel cells, the amounts of carbon dioxide emitted during fuel use are highest (0.4 to 0.8 kg/kWh) for partially oxidised fuels, partly because this process produces less hydrogen per mole than reforming and partly because the reaction produces more CO_2 per mole, see chapter 5. The next highest values are for externally reformed fuels: RME with the highest, followed by methanol, diesel, ethanol and petrol (0.3 to 0.6 kg/kWh), all within a 10% band at any one efficiency; then propane about 10% lower and methane the lowest of all (0.4 to 0.7 kg/kWh). Internally reformed fuels have lower CO_2 emissions during usage (0.3 to 0.5 kg/kWh) because the heat of

reformation is provided from the waste heat from high temperature fuels cells.

The total CO_2 emissions from fuel cells are the sum of those emitted during usage and those emitted during fuel production (0.4 to 0.9 kg/kWh for partially oxidised fuels, 0.3 to 0.8 for reformed fuels. For biofuels, if the carbon dioxide during use is offset against that absorbed by the biocrop during growth, then the total CO_2 emissions are significantly reduced ie, by 79% for RME, 76% for bioethanol and 72% for biomethanol. The fuel with lowest carbon dioxide emission is hydrogen, where emissions are from fuel production (0.07 to 0.1 kg/kWh).

7.5.2.2 IC ENGINES (CO)

When compared with conventional fuels such as petrol and diesel, carbon dioxide exhaust emissions are comparable for most fuels (1 to 1.4 kg/kWh) and lowest for IC engines using natural gas or methane (0.6 to 0.9). Some improvement (0.8 to 1.1) is given by using propane, or methanol produced from natural gas. However, this method of producing methanol is only worthwhile if a liquid fuel is preferred to carrying the natural gas. When fuel production emissions are included, the biofuels have the highest values due to the high values during the agricultural and processing stages.

7.5.2.3 BATTERIES (CO_2)

Results for recharging batteries using the emissions from the current mix of electric power generating stations are shown in Tables A.3 to A.10 for comparison. The carbon dioxide emissions (0.7 to 1.1 kg/kWh) are comparable with those for IC engines and thus, although vehicle emissions are zero, the pollution is simply transferred to that from the power generation stations.

reformation is provided from the waste heat from high temperature fuels cells.

The total CO_2 emissions from fuel cells are the sum of those emitted during usage and those emitted during fuel production (0.4 to 0.9 kg/kWh for partially oxidised fuels, 0.3 to 0.8 for reformed fuels. For biofuels, if the carbon dioxide during use is offset against that absorbed by the biocrop during growth, then the total CO_2 emissions are significantly reduced ie, by 79% for RME, 76% for bioethanol and 72% for biomethanol. The fuel with lowest carbon dioxide emission is hydrogen, where emissions are from fuel production (0.07 to 0.1 kg/kWh).

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7.5.2.3 BATTERIES (CO_2)

Results for recharging batteries using the emissions from the current mix of electric power generating stations are shown in Tables A.3 to A.10 for comparison. The carbon dioxide emissions (0.7 to 1.1 kg/kWh) are comparable with those for IC engines and thus, although vehicle emissions are zero, the pollution is simply transferred to that from the power generation stations.

7.5.2.4 COMPARISON OF CARBON DIOXIDE EMISSIONS

In general, fuel cells have lower carbon dioxide emissions than IC engines because of their higher efficiency. However, for partially oxidised fuels they are comparable with those from IC engines and are only significantly reduced for reformed fuels, particularly with internal reforming in high temperature fuel cells. In IC engines, when compared with diesel and petrol, CO_2 exhaust emissions are reduced for industrially produced methanol, propane and methane, and increased for the biofuels. However, if the carbon dioxide during use is offset against that absorbed by the biocrop during growth, then the total CO_2 emissions are significantly reduced ie, by 81% for bioethanol and RME, and by 69% for biomethanol.

The most significant reductions using fossil fuels with fuel cells are obtained with natural gas or methane. The ideal fuel is hydrogen, where CO_2 emissions are confined to the fuel production processes and, for fuel cell efficiencies above about 60%, are an order of magnitude less than those from IC engines. However, in order to avoid a new infrastructure for the distribution of a gaseous fuel to road users, a compromise would be to use a conventional liquid fuel such as diesel for inboard reforming. This would produce CO_2 emissions about 50% lower than those from petrol and diesel IC engines, and slightly lower if internally reformed in a high temperature fuel cell system using a solid oxide type.

Emissions from electric power stations for recharging battery driven vehicles are comparable with those from IC engines.

7.5.3 CARBON MONOXIDE

Carbon monoxide emissions from vehicle exhausts are a health hazard and guidelines are to limit concentrations to 10 ppm averaged over 8 hours (Chapter 1).

7.5.3.1 FUEL CELLS (CO)

It is assumed that, due to the intolerance or low tolerance of fuel cells to contamination by carbon monoxide, the only CO emissions permitted during fuel usage are from the combustion of additional fuel to provide the heat of reformation for externally reformed fuels. These emissions could, in practice, be reduced by appropriate control of the burner flue gases but are included for completeness. For the same reason, it is assumed that there are no CO emissions from partially oxidised fuels, or that any residual CO is oxidised before the fuel gas is passed into the fuel cell. Internally reformed fuels also are assumed to produce no residual carbon monoxide. Thus, the only CO emissions for partially oxidised or internally reformed fuels are produced during fuel production.

During usage, the highest CO emissions for reformed fuels from the reformer heater are for petrol (0.5 to 0.7 g/kWh) followed by the biofuels bioethanol (0.4 to 0.75) and RME (0.3 to 0.6), then diesel (0.25 to 0.4), biomethanol (0.2 to 0.3), methane and propane, the latter two being almost the same (0.05 to .07). These differences are due to the differences in the amounts emitted from burning the various fuels in the reformer heater, with relatively large amounts from ethanol, diesel and RME.

The total CO emissions for fuel cells are the sum of those emitted during usage and those emitted during fuel production. Carbon monoxide emissions are highest (0.6 to 1.6 g/kWh) for the biofuels, reformed bioethanol and RME, partially oxidised RME and internally reformed bioethanol due to the relatively large amounts emitted during the fuel production phases. These are followed by reformed petrol, internally reformed RME, reformed biomethanol and reformed diesel (0.3 to 0.9). Total CO emissions are further reduced (0.1 to 0.3) for methanol (produced from natural gas), internally reformed biomethanol and bioethanol, propane and methane. Petrol and diesel have relatively large total CO emissions because of the amounts emitted from the additional fuel burnt to provide the heat of reformation. Finally, the least total CO emissions from the manufacture of fossil fuels are for partially oxidised and internally reformed

hydrocarbons and methanol (produced from natural gas) (0.01 to 0.06 g/kWh) because the heat of reformation during usage is supplied from the waste heat of high temperature fuel cells rather than from burning additional fuel. The emissions from the production of hydrogen from the current mix of electric power stations is about mid way in this group.

7.5.3.2 IC ENGINES (CO)

Carbon monoxide emissions for IC engines are highest (11 to 15 g/kWh) for petrol and bioethanol, and reduced for diesel and RME (5 to 8), methanol and natural gas (3 to 5) and LPG (1 to 2).

7.5.3.3 BATTERIES (CO)

The amounts of CO emitted from the current mix of electric power stations assumed for recharging batteries (0.2 to 0.3) are very much less than for IC engines and low compared with those from reformer heaters for fuel cells.

7.5.3.4 COMPARISON OF CARBON MONOXIDE EMISSIONS

Fuel cells have significantly less CO emissions than IC engines, and are due either to that from using a significantly smaller amount of fuel to provide the heat of reformation or from the production processes. The CO emissions from fuel reformer heaters could be reduced to insignificant amounts by advanced control of the flue gases. The greatest reduction in CO emissions are obtained by using hydrogen, partially oxidised or internally reformed fuels, the lowest being for methane. Comments in section 7.5.2.4 above, on the use of diesel or petrol in high temperature fuel cell systems also apply to this section.

7.5.4 METHANE

Methane is a major greenhouse gas (Chapter 1) mainly produced biologically and by leakages from fossil fuel extraction, during distribution and at filling stations.

7.5.4.1 FUEL CELLS (CH_4)

The same assumption is made as for CO emissions ie, that the only methane emitted during fuel usage is from the combustion of the small amount of fuel used to provide the heat of reformation for externally reformed fuels. The largest amount (1 to 2 g/kWh) is for methane, consisting of unburnt fuel in the flue gases of the reformer heater. This amount is comparable with that emitted during the usage of other fuels in IC engines (0.5 to 2). The amounts of methane emitted from the reformer heaters for other fuels are at least an order of magnitude less (0.002 to 0.009), with the least amount being for ethanol, petrol and diesel (0.002 to 0.005).

The total amounts of methane are critically dependent upon the emissions from the fuel production processes, and all are at least an order of magnitude greater than from fuel usage. The highest amounts are for methane and methanol (1.1 to 2.1 g/kWh), due mainly to distribution losses. Methane emissions for hydrogen also are relatively high (0.3 to 0.4) due to those from the current mix of electric power stations assumed for production by electrolysis. The total methane emissions for all of the remaining fuels are relatively low (0.07 to 0.2), with internally reformed diesel having the lowest values of the fossil fuels (0.07 to 0.1), the least amounts being for the biofuels (0.004 to 0.008). It should be noted that there are no methane emissions for RME.

7.5.4.2 IC ENGINES (CH_4)

Methane emitted from the exhausts of IC engines, except when it is used as a fuel, is an order of magnitude greater than that from fuel cells. For methane as fuel the

methane exhaust emissions are 3 to 4.3 g/kWh. However (except for methane and methanol, when methane emissions from production processes are taken into account, the total values are comparable with those for fuel cells.

7.5.4.3 BATTERIES (CH_4)

Emissions of methane from electric power stations assumed for recharging batteries are, except for methane, greater (2 to 3) than those from IC engines.

7.5.4.4 COMPARISON OF METHANE EMISSIONS

Fuel reformer heaters for fuel cells emit significantly less methane compared with IC engines because of the much smaller amounts of fuels used. In practice, this could be reduced to near zero by suitable control of the reformer flue gases. However, the greatest amounts of methane are produced from the fuel production processes for petrol, diesel and LPG, and the dstribution losses for natural gas, both as a fuel and when used to produce methanol. It should be noted that there are no methane emissions for the biofuels, except small amounts from the reformer heater for biomethanol (0.01 g/kg of methanol, and unknown but equally small values for ethanol and RME).

7.5.5 NON METHANE VOLATILE ORGANIC COMPOUNDS (NMVOC)

7.5.5.1 FUEL CELLS (NMVOC)

The same assumption made for CO and methane emissions above, that the only emissions during fuel usage of reformed fuels are from the small amounts of fuel used for the reformer heater, applies to NMVOCs. The largest amount (0.5 to 0.7 g/kWh) is for petrol, due to the relatively large amount emitted from burning the fuel in the reformer heater. The next largest values are for ethanol (0.1 to 0.16), methanol (0.06 to 0.08), and diesel and RME (0.04 to 0.06). Although diesel emits slightly more

NMVOC/kg from the reformer heater than methanol or RME, the net NMVOC is smaller because reformed diesel produces more hydrogen per mole.

The total amounts of NMVOC for fuel cells are highest for biomethanol (2.4 to 3.4 g/kWh), petrol and bioethanol systems (1 to 2.3) due to the relatively high values of petrol losses during its distribution, and emissions during crop processing for biomethanol and bioethanol. The amounts for all fuels (0.2 to 1.0) are lowest for diesel, propane and RME (0.3 to 0.7) and methane (0.2 to 0.3). Hydrogen fuel has the lowest total amount (0.004 to 0.006) due the low NMVOC emissions from the current mix of electric power stations assumed for fuel production by electrolysis.

7.5.5.2 IC ENGINES (NMVOC)

NMVOCs emitted from the exhaust of IC engines is highest (1.7 to 2.4 g/kWh) for RME and lowest (0.3 to 0.4) for methane. However, when production processes are taken into account, the total amounts are highest (3.5 to 4.8) for biomethanol, due to the relatively high amount emitted during crop processing, and lowest (1.4 to 2) for LPG.

7.5.5.3 BATTERIES (NMVOC)

The low NMVOCs emitted from electric power stations assumed for recharging battery driven vehicles give relatively low values (0.027 to 0.055) compared with fuels.

7.5.5.4 COMPARISON OF NMVOC EMISSIONS

Except for petrol, the NMVOC emissions from fuel cell system fuel reformers are significantly less than those from the exhausts of IC engines. As for both CO and methane above, this is because of the much lower amounts of fuel used in the reformer heaters. Again, as for CO and methane, this emission could be reduced to insignificant amounts by treatment of the reformer flue gases. However, these emissions are at least

an order of magnitude less than those from fuel production. The production of hydrogen assuming NMVOC emissions from the current mix of electric power stations gives the lowest value.

7.5.5 NITROGEN OXIDES (NOx)

Oxides of nitrogen, mainly from vehicle exhausts, are a hazard to health and guidelines are to limit concentrations to 105 ppb over one hour (Chapter 1).

7.5.5.1 FUEL CELLS (NOx)

The same assumption made for CO, methane and NMVOC emissions above, that the only emissions during fuel usage of reformed fuels are from the small amounts of fuel used for the reformer heater, also applies to NOx. Maximum emissions are for the biofuels (0.26 to 0.4 g/kWh), diesel (0.18 to 0.25) and methanol (0.16 to 0.22) due to the relatively high amounts emitted from burning these fuels in the reformer heater. Values for other fuels are between 0.08 and 0.12. The relatively large amounts of NOx emitted during the crop growth and processing stages for the biofuels give relatively large amounts (0.5 to 2) for total NOx emissions. Those for other fuels are between 0.05 and 0.5, with the least amounts (0.05 to 0.2) for partially oxidised and internally reformed methane and internally reformed methanol. The amount (0.2 to 0.3) for hydrogen is higher than for many of the fuels, when these are internally reformed or partially oxidised, due to the relatively high NOx emissions from electric power stations used for production by electrolysis.

7.5.5.2 IC ENGINES (NOx)

Vehicle exhaust NOx emissions are highest (4 to 8 g/kWh) for bioethanol, RME and diesel and lowest (2 to 4) for petrol and propane. Emissions from fuel production processes change the order, with highest values for bioethanol and RME (7 to 11), diesel and biomethanol (4 to 6) with methanol, propane, methane and petrol having the

lowest values (3 to 5).

7.5.5.3 BATTERIES (NOx)

The relatively high values (1.8 to 3 g/kWh) of NOx emitted from electric power stations is reflected in the values for battery recharging.

7.5.5.4 COMPARISON OF NITROGEN OXIDE EMISSIONS

The NOx emissions from fuel cell systems using the fossil fuels are significantly less than those from IC engines, particularly for internally reformed fuels in high temperature fuel cells. In the same way as for CO, methane and NMVOC emissions, the NOx emissions from fuel reformer heaters could be reduced to insignificant values by treatment of the flue gases.

7.5.6 NITROUS OXIDE (N_2O

7.5.6.1 FUEL CELLS, IC ENGINES AND BATTERIES (N_2O)

Nitrous oxide is a greenhouse gas as well as being a hazard to health (Chapter1). The only N_2O emissions during usage are from the reformer heater for the reformed fossil fuels petrol (0.009 to 0.012 g/kWh) and diesel (0.0012 to 0.0009), and there are none or only negligible amounts from fossil fuel production phases. There are no N_2O emissions from either the combustion or production phases of the biofuels RME, bioethanol and biomethanol. Of the total emissions (production plus usage), those from the production of hydrogen using electrolysis are the lowest (0.006 to 0.008). NO_x emissions from the use of petrol in IC engines (0.2 to 0.3) is an order of magnitude larger than that for diesel fuel (0.02 to 0.03). Greatest emissions (0.03 to 0.07) are from the assumed mix of electric power stations used to recharge battery driven vehicles. As for the other emissions above, emitted N_2O from the fuel reformer heater during the use of reformed fuels could be reduced to negligible quantities by treatment of the flue gases.

7.5.7 SULPHUR DIOXIDE (SO_2)

Sulphur dioxide is a danger to health and guidelines will limit concentrations to 100 ppb over 15 minutes. (Chapter 1).

7.5.7.1 FUEL CELLS (SO_2)

It is assumed that their are negligible sulphur dioxide emissions from the combustion of fuels in IC engines or fuel reformer heaters for reformed fuels in fuel cells; fuels would need to be desulphurized for use with fuel cells except possibly for some solid oxide types. Thus, emissions are from the production of fuels and the total depends only on this amount and the fuel consumption. Emissions from electric power stations are relatively high, giving a high value (0.8 to 1.1 g/kWh for hydrogen). The biofuels bioethanol and RME also have high SO_2 emissions (0.6 to 1.4) for the production phases, particularly for crop processing. Other fuels have lower SO_2 emissions for their production phases (petrol, 0.4 to 0.7, diesel and propane 0.2 to 0.4, methanol and methane 0.13 to 0.25). The fuel consumptions also affect the overall results; internally reformed fuels generally have the lower values compared with partial oxidation or with reforming using fuel in an external reformer heater.

7.5.7.2 IC ENGINES (SO_2)

Results for IC engines follow the same pattern as for fuel cells but with higher values due to the higher fuel consumptions.

7.5.7.3 BATTERIES (SO_2)

The emissions from electric power stations used to recharge battery driven vehicles result in the highest values of SO_2 (5 to 9 kg/kWh).

7.5.7.4 COMPARISON OF SULPHUR DIOXIDE EMISSIONS

The sulphur dioxide emissions for all the fuels are assumed to be produced during the fuel manufacturing phases. For fuel cells with efficiencies of 50% to 60% the emissions for the biofuels and bioethanol and RME are comparable with those for RME in IC engines, but are lower than those for ethanol in IC engines. Those for 55% to 60% fuel cells with internally reformed RME, partially oxidised, internally reformed and reformed petrol and partially oxidised propane and diesel are comparable with those for petrol and diesel in IC engines. At the same fuel cell efficiencies, those for reformed and internally reformed propane and diesel and partially oxidised methane are comparable those for propane and bioethanol in IC engines. Those for reformed and internally reformed have slightly less values. Sulphur dioxide emissions from the recharging of battery driven vehicles are at least one order of magnitude higher.

7.5.8 PARTICULATE MATTER

Particulates, produced from diesel engines and other sources are a health hazard, and guidelines will limit concentrations to 50 mg/m^3 over 24 hours (Chapter 1).

7.5.8.1 FUEL CELLS (PM)

During the usage phase, particulate matter is only emitted from the reformer heaters for reformed fuels (0.02 to 0.04 g/kWh for diesel and RME, 0.01 to 0.02 for methanol, ethanol and petrol, 0.005 to 0.01 for propane and methane). These could be reduced to insignificant values by advanced treatment of the flue gases. Particulate emissions from fuel production phases increase these amounts (0.04 to 0.09 for biomethanol, 0.13 to 0.28 for the other biofuls, 0.01 to 0.04 for hydrogen and externally reformed diesel, petrol and propane). When partially oxidised or internally reformed, fuels only have emissions from the fuel production phases, the biofuels bioethanol and RME have the highest values due to PM emissions during the agricultural and fuel processing phases, as indicated above. The lowest values of PM emissions are for reformed

methane, partially oxidised and internally reformed propane (0.0025 to 0.0055), partially oxidised petrol and diesel and internally reformed propane, petrol and diesel (0.0005 to 0.001).

7.5.8.2 IC ENGINES (PM)

During fuel usage, the highest PM emissions (0.5 to 0.9 g/kWh) are from diesel and RME; the other fuels having relatively lower values (0.15 to 0.4), that for methane being the lowest (0.08 to 0.12). Except for diesel, petrol and methane, PM emissions from fuel production are similar to those emitted during fuel usage.

7.5.8.3 BATTERIES (PM)

Particulates from electric power stations result in relatively high emissions for recharging battery driven vehicles (0.1 to 0.2 kg/kWh).

7.5.8.4 COMPARISON OF PARTICULATE MATERIAL EMISSIONS

The relatively high total PM emissions from IC engines can be reduced by using biomethanol, propane or methane, but are increased by the use of biomethanol, diesel or bioethanol when compared with petrol.

Fuel cell systems using RME, bioethanol and reformed biomethanol are comparable with IC engines using propane, but have greater PM emissions than IC engines using petrol. Emissions from fuel cell systems using biomethanol are comparable with IC engines using methane.

The PM emissions from the current mix of electric power stations are comparable with the highest for fuel cells using RME and bioethanol.

7.5.9 HYDROGEN FROM DEDICATED LOW EMISSION POWER SOURCES

A large number of papers have been written about the possibilities of a future hydrogen economy where electrical power generation and transport are fuelled by hydrogen, which could be produced by the electrolysis of water. Any publication such as the present thesis on energy and environment would not be complete without some comment in this area. Hence calculations have been made (section 7.4.2.4, above) for low emission electrical power generation stations such as nuclear and those using renewable resources.

Because of the lack of data on emissions produced during construction and operation of these plants, these are calculated for carbon dioxide only, using the data from section 7.3.8, above. The results are given in Table A.11 in Appendix A as grammes of CO_2/kWh of energy from a fuel cell system using hydrogen against fuel cell efficiency. Results for the current mix of power stations and nuclear power plants only, are included for comparison. Those for renewable energy sources are significantly lower than those from the production of hydrogen using the current mix of power stations or from the manufacture of other fuels.

However, until legislation forces the use of fossil fuels to be phased out, it is unlikely that renewable energy sources will be used to replace conventional electrical power stations except in areas where either hydroelectric or geothermal energy is readily available, and nuclear energy has its own unique pollution problems. Possibly, a more advantageous way to introduce fuel cells would be to phase them in as electrical power generation stations using reformed fossil fuels to provide power for recharging battery driven vehicles. This is considered below and in more detail in chapter 9.

7.6 WATER FROM FUEL CELL REACTION

The amount of water produced from the fuel cell calculated from the fuel cell reaction is 36.032/4.032 = 8.937 kg H_2O/kg H_2 used. For the efficiencies (0.45 to 0.65) used in the above discussion, this amounts to 0.596 to 0.413 kg or litres of water per kWh of energy developed by the fuel cell. In a system using partial oxidation plus a steam shift reaction or steam reforming to produce the hydrogen, this water could be used to provide the steam for the fuel processing reactions. However, quantities required vary, depending upon the type of fuel, and are calculated from the chemical reactions. The results are shown in Table 7.17.

TABLE 7.17
Water Required (kgH_2O/kgH_2)

Fuel	Steam Reforming plus CO Shift	Partial Oxidation plus CO Shift
Methane	4.468	2.979
Propane	5.362	3.840
Petrol	5.687	4.170
Diesel	5.836	4.333
RME	11.806	4.528
Methanol	2.979	
Ethanol	4.468	

It is seen from table 7.17 that, except for steam reforming of RME, sufficient water is produced from the fuel cell reaction to provide the steam required for fuel processing. Thus, excess water is produced for most fuels, as shown in Table 7.18.

TABLE 7.18
Excess Water (kgH_2O/kgH_2)

Fuel	Steam Reforming plus CO Shift	Partial Oxidation plus CO Shift
Methane	4.469	5.958
Propane	3.575	5.097
Petrol	5.687	4.767
Diesel	3.101	4.604
RME	-2.869	4.409
Methanol	5.958	
Ethanol	4.469	

7.7 RELATION OF RESULTS TO FURTHER WORK

The results given in this chapter can be used for fuel cell systems in both the transportation and electrical power generation sectors.

For through life emissions of transportation systems, consideration needs to be given to the efficiencies of the power units, driving cycles, average speed and total mileage for particular sizes of vehicles. These calculations are carried out in the next chapter for selected public transport systems using the above results.

Consideration of how best to introduce fuel cells is considered later in chapter 9, and one of the options is the use of fuel cell power electric generation stations to recharge battery driven public transport vehicles. The results in this chapter have shown that the emissions from fuel cell systems using reformed natural gas or methane and diesel are amongst the lowest of the fuels considered. Also, reformers for these fuels,

particularly natural gas, are being developed and natural gas reformers have been demonstrated widely in the fuel cell generation sector. Because of this, and since diesel is already widely used for public transport and natural gas is being demonstrated, these are considered to be ideal fuels for use in power generation stations dedicated to recharging public transport electric vehicles. The above results for natural gas and diesel will be used for the calculations of emissions from the fuel cell power stations. In this way, electric vehicles could be introduced alongside diesel vehicles whilst using the same fuel infrastructure.

8. THROUGH LIFE ENERGY AND EMISSIONS

8.1 INTRODUCTION

This chapter calculates the through life emissions from selected transport systems.

Values for system production, distribution and disposal are derived from published data, see section 8.2 below.

Those for the production plus usage of fuels in transport vehicles are calculated by the author using the results from the previous chapter. These are made in terms of amounts of emitted pollutant per kW of energy produced by the transport vehicle power system. Transmission efficiencies are ignored, but account is taken of the efficiency of the power system, eg IC engine, battery or fuel cell.

8.2 SYSTEM PRODUCTION

To assess the energy requirements during the production of different systems information on components, materials and their amounts were requested from manufacturers. However, information on fuel cell materials was not readily available, possibly due to competition between manufacturers.

One estimate for the energy used, and emissions produced, for various transport systems include the production of proton exchange membrane fuel cells (PA Consulting, 1992) where it is stated that *Information from fuel cell manufactures about the component materials in a PEMFC system and the amounts needed in a 20 kW system has been used to calculate the environmental impacts of the production of the component materials* without naming the manufacturers. The calculations (PA Consulting, 1992) were made from the energy used to manufacture unit amount of each material (Boustead and Hancock, 1979); the emissions given off to the

atmosphere during production also were derived from published data (Boustead and Hancock, 1979), (Hocking, 1986) and EMPA, 1984). Also, in PA Consulting, (1992) it is stated that *For the purpose of calculating emissions from the generation of energy used in manufacturing, the mix of fuel types ... assumed ...is the average mix in 1989 in the UK for primary energy consumption excluding motor gasoline.*

Other systems included, and compared with the fuel cell system (PA Consulting, 1992) are for an IC engine, a lead acid battery, a sodium sulphur battery, a sodium nickel chloride battery, an IC engine/lead acid battery and a phosphoric acid fuel cell/lead acid battery.

In addition, an estimate of the energy from the manufacture of each system from its component parts are included (PA Consulting Group, 1992). For this estimate, an overall additional 25% for both energy and emissions has been assumed (Appleby and Foulkes, 1989) and (Deluchi, 1991).

Results (PA Consulting Group, 1992) are given in MJ for energy and in CO_2-Equivalent for emissions, and summarised in Table 8.1. Thus, for the purpose of this thesis, in which the use of CO_2-Equivalents has been avoided, see chapter 2, and vehicles considered are of a different size, comparisons are made by presenting values relative to the IC engine. These comparisons are given in Table 8.2.

TABLE 8.1
Production Energies and CO_2-Equivalents
(Based on PA Consulting, 1992)

System	Energy (MJ)	CO_2-Equivalent (kg)
IC Engine (1.6l)	15400	601
Pb Acid Battery (12kWh)	7840	1482
NaS Battery (12kWh)	12750	475
NaNi Chloride Batt. (12kWh)	15375	393
PEM Fuel Cell (20kW)	24130	394

TABLE 8.2
Relative Production Energies and CO_2-Equivalents
(Based on PA Consulting, 1992)

System	Energy	CO_2-Equivalent
IC Engine	1.0	1.0
Pb Acid Battery	0.509	2.466
NaS Battery	0.828	0.790
NaNi Chloride Battery	0.998	0.654
PEM Fuel Cell	1.567	0.656

8.3 SYSTEM USAGE

8.3.1 INTRODUCTION

Preliminary results for carbon dioxide emissions from the various fuels considered have been published (Adams, 1996a and 1996b). In these preliminary results the carbon dioxide emissions for fuel production were derived from earlier published data (IPCC, 1991) and (Klaiber, 1995).

8.3.2 THROUGH LIFE CALCULATIONS

The results in chapter 7 are given in terms of quantity of energy or pollutant per kWh of energy produced by a vehicle power system. Thus, through life estimates need to take account of the average driving cycle and lifetime, and these will depend upon the type of vehicle chosen for study. Previous work on emissions from transport vehicles (eg IPCC, 1991 and 1995) present results in the form of values per km driven for particular vehicles.

Calculations in the present chapter are made using an assumed lifetime in km and average speed based on an average driving cycle, as follows:

$$\text{Lifetime Quan./kW} = (\text{Quan./kWh})*(\text{km of Life})/(\text{Av. Speed}) \quad [1]$$

from which values for vehicles of any particular power can easily be calculated.

Results for the fuels considered (hydrogen, petroleum, diesel fuel, natural gas, LPG, ethanol, methanol and RME) and for recharging battery driven vehicles, are given in Tables A.12 to A.19 in Appendix A. These are derived from the results in Tables A.3 to A.11 Appendix A, assuming an average driving cycle of 30 km/hr (for urban buses) and lifetime running didtance of of 100,000 km.

Up to now this thesis has concentrated on comparing energy and emissions from using alternative fuels in IC engines, using the same fuels for fuel cells and recharging batteries. However, as stated in chapter 2, whilst alternate fuels and high efficiency fuel cells are one way of reducing pollution from transport, it is recognised also that a reduction in the number of vehicles is needed to reduce pollution as well as road congestion. This is particularly relevant to certain times of day and locations, such as the morning and evening "rush hours" and city and urban areas. Thus, any new fuel or system is better applied in the first to instance public transport rather than private

vehicles. This supports a strategy to improve and enhance the use of public transport.

The results in Tables A.12 to A.19 in Appendix A for 35% efficient IC engines, 60% efficient fuel cells and 70% batteries are plotted in Figures 8.1 to 8.8. The efficiencies are chosen for typical urban diesel buses, PEM fuel cells and lead acid or nickel iron batteries. Values for a particular bus power can be obtained simply by multiplying the individual results by the power unit power in kW.

8.3.3 DISCUSSION OF RESULTS

8.3.3.1 CARBON DIOXIDE

The results indicate that CO_2 emissions from the current mix of power stations used to recharge battery driven vehicles are comparable to those from IC engines (Figure 8.1). Total emissions from fuel cell systems using biofuels are either comparable with or, up to about 50% lower than from IC engines. Those from IC engines using biofuels are higher than those from fossil fuels.

However, if the CO_2 emitted during usage is offset against that absorbed during the crop growth period then the net emissions for biofuels are reduced to the much lower values emitted during the fuel production phases. This is only relevant over a long time scale and large areas of land are required to give a significant reduction in CO_2 emissions from the transport sector (see section 8.3.3.9, below).

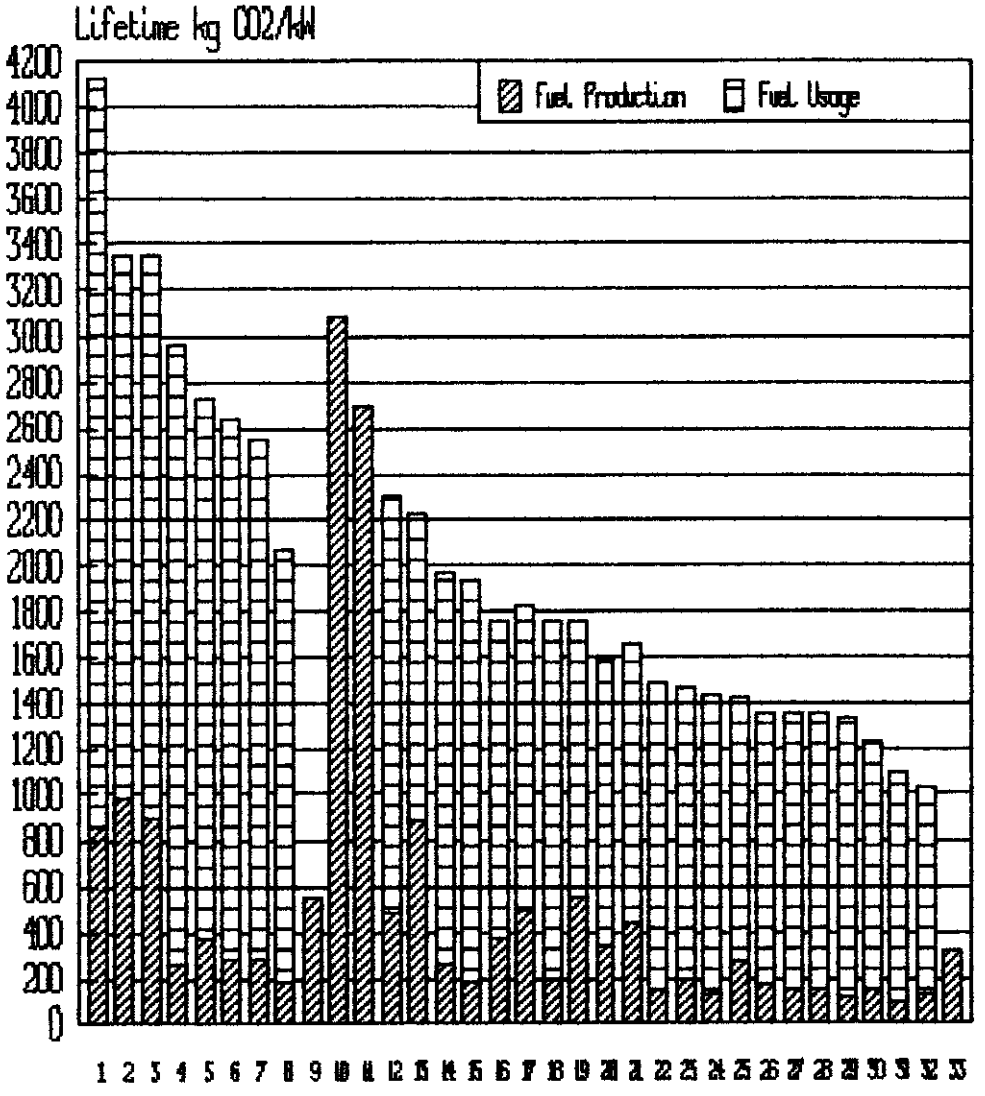
Significant reductions in total CO_2 emissions (below 1500 kg/kW, say) from fuel cell systems are made for reformed methanol, petrol, diesel, propane, methane and from hydrogen (Figure 8.1). The most significant reductions are made using internally reformed methane and hydrogen.

KEY TO FIGURE 8.1

1 ICE RME
2 ICE Biomethanol
3 ICE Bioethanol
4 ICE Diesel
5 ICE Petrol
6 ICE Methanol
7 ICE Propane
8 ICE Methane
9 ICE Hydrogen (Electrolysis)
10 Batt. CHarge (24hrs)
11 Batt. Charge (Night)
12 FC RME (Partial Oxidation)
13 FC Biomethanol (Steam Reformed)
14 FC Petrol (Partial Oxidation)
15 FC Diesel (Partial Oxidation)
16 FC RME (Steam Reformed)6
17 FC Bioethanol (Steam Reformed)
18 FC Propane (Partial Oxidation)
19 FC Biomethanol (Internally Reformed)
20 FC RME (Internally Reformed)
21 FC Bioethanol (Internally Reformed)
22 FC Methanol (Steam Reformed)
23 FC Petrol (Steam Reformed)
24 FC Diesel (Steam Reformed)
25 FC Propane (Steam Reformed)
26 FC Methane (Sream Reformed)
27 FC Petrol (Internally Reformed)
28 FC Diesel (Internally Reformed)
29 FC Methanol (Internally Reformed)
30 FC Propane (Internally Reformed)
31 FC Methane (Steam Reformed)
32 FC Methane (Internally Reformed)
33 Hydrogen (Electrolysis)

Figure 8.1 Lifetime kg CO2/kW for Urban Buses

1-9 35% ICE, 10-11 70% Battery, 12-33 60% Fuel Cell



8.3.3.2 CARBON MONOXIDE

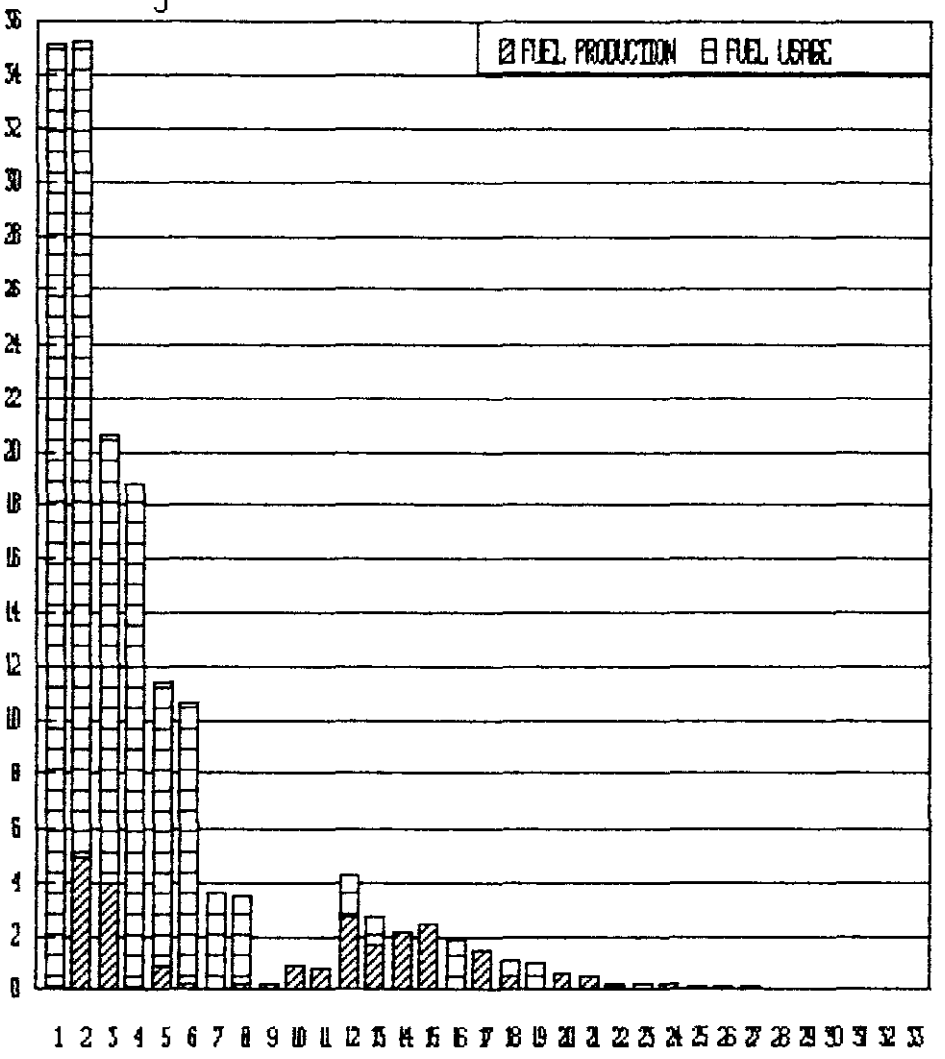
In IC engines, some reduction in CO emission is made when RME is compared with petrol, are comparable when compared with diesel. The highest reductions are for methane and propane (Figure 8.2). Significant reductions (below 1g/kW, say) are made for battery driven vehicles recharged from current power stations and from fuel cell systems using diesel fuel, methanol, propane, petrol, methane and hydrogen.

KEY TO FIGURE 8.2

1 ICE Petrol
2 ICE Bioethanol
3 ICE RME
4 ICE Diesel
5 ICE Biomethanol
6 ICE Methanol
7 ICE Methane
8 ICE Propane
9 ICE Hydrogen (Electrolysis)
10 Batt. Charge (24hrs)
11 Batt. Charge (Night)
12 FC Bioethanol (Reformed)
13 FC RME (Reformed)
14 FC RME (Partial Oxidation)
15 FC Bioethanol (Internally Reformed
16 FC Petrol (Reformed)
17 FC RME (Internally Reformed)
18 FC Diesel (Reformed)
19 FC Methanol (Reformed)
20 FC Biomethanol (Internally Reforme
21 FC Biomethanol (Internally Reforme
22 FC Propane (Reformed)
23 FC Methane (Reformed)
24 FC Propane (Partial Oxidation)
25 FC Petrol (Partial Oxidation)
26 FC Propane (Internally Reformed)
27 FC Diesel (Partial Oxidation)
28 FC Hydrogen (Electrolysis)
29 FC Petrol (Internally Reformed)
30 FC Methanol (Internally Reformed)
31 FC Diesel (Internally Reformed)
32 FC Methane (Partial Oxidatiuon)
33 FC Methane (Reformed)

Figure 8.2 Lifetime g CO/kW for Urban Buses

1-9 35% ICE, 10-11 70% Battery, 12-33 60% Fuel Cell



8.3.3.3 METHANE

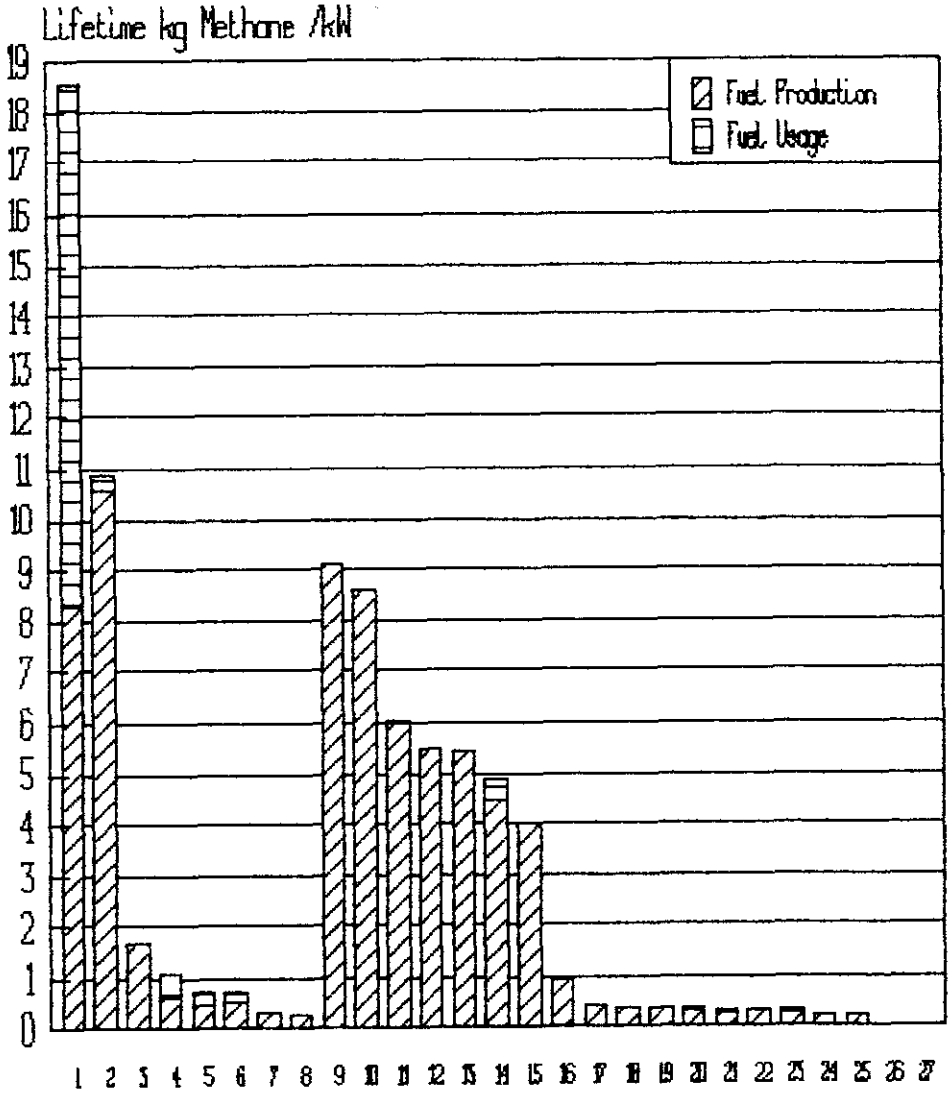
Methane emissions are highest from systems using methane and methanol as a fuel due to the amounts lost from leakage during the fuel production phases, and battery systems (Figure 8.3). All other systems produce significantly less methane. The most significant reductions are from fuel cell systems using steam reformed biomethanol and bioethanol. None, or insignificant amounts of methane are emitted from systems using RME, ethanol and bioethanol.

KEY TO FIGURE 8.3

1 ICE Methane
2 ICE Methanol
3 ICE Hydrogen (Electrolysis)
4 ICE Propane
5 ICE Petrol
6 ICE Diesel
7 ICE Biomethanol
8 ICE Bioethanol
9 Batt. Charge (24hrs)
10 Batt. Charge (Night)
11 FC Methanol (Reformed)
12 FC Methanol (Int. Ref.)
13 FC Methane (Partial Oxidation)
14 FC Methane (Reformed)
15 FC Methane (Internally Reformed)
16 FC Hydrogen (Electrolysis)
17 FC Propane (Partial Oxidation)
18 FC Petrol (Partial Oxidation)
19 FC Diesel (Partial Oxidation)
20 FC Propane (Reformed)
21 FC Petrol (Reformed)
22 FC Propane (Int. Ref.)
23 FC Diesel (Reformed)
24 FC Petrol (Int. Ref.)
25 FC Diesel (Int. Ref.)
26 FC Biomethanol (Reformed)
27 FC Bioethanol (Reformed)

Figure 8.3 Lifetime kg Methane/kW for Urban Buses

1-8 35% ICE, 9-10 70% Battery, 10-27 60% Fuel Cell



8.3.3.4 NON METHANE VOLATILE ORGANIC COMPOUNDS

When compared with conventional fuels, NMVOC emissions are increased for IC engines using biofuels and reduced for propane and methane and emissions from fuel cell systems using biomethanol are increased (Figure 8.4).

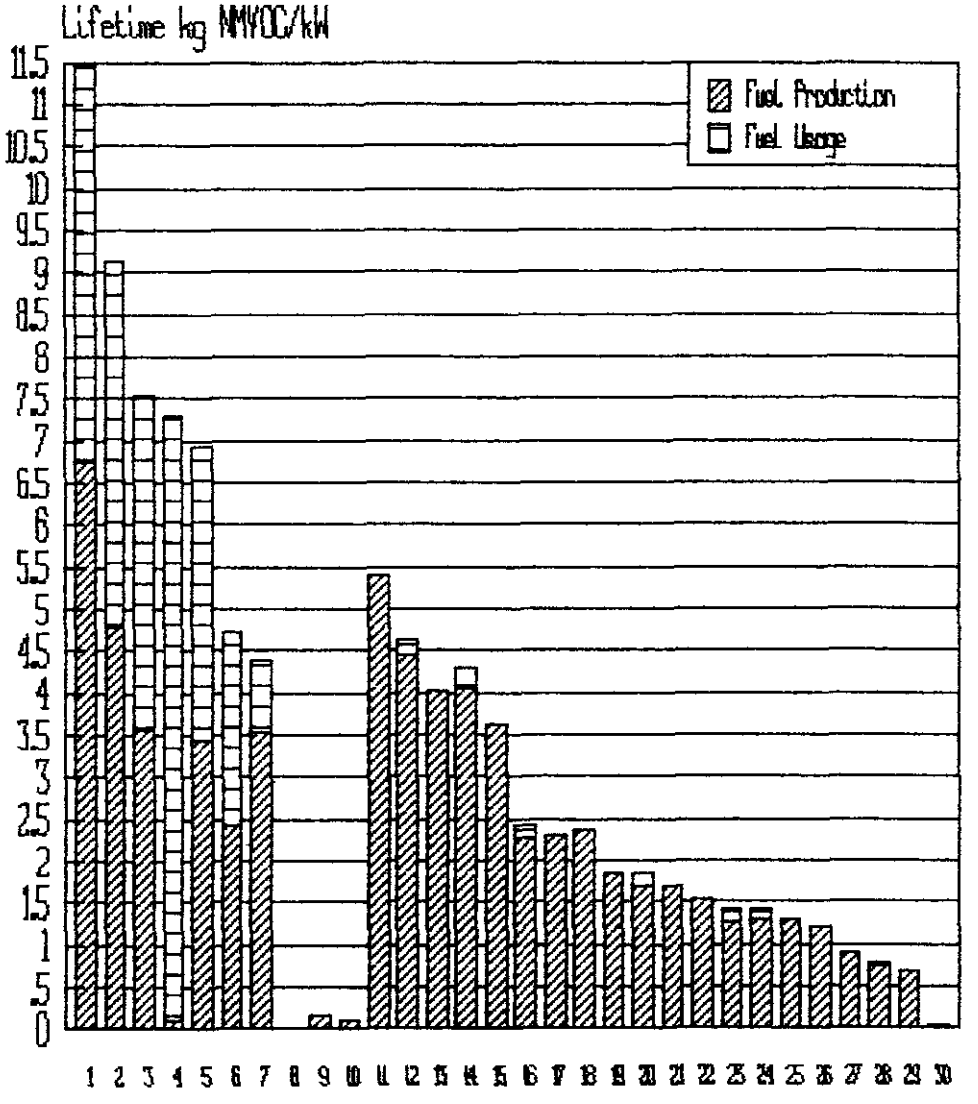
Significant reductions in NMVOC emissions are made for fuel cell systems using diesel, bioethanol, RME, propane and methane, and extremely low amounts are emitted from battery systems and fuel cell systems using hydrogen.

KEY TO FIGURE 8.4

1 ICE Diesel
2 ICE Bioethanol
3 ICE Biomethanol
4 ICE Petrol
5 ICE RME
6 ICE Propane
7 ICE Methane
8 ICE Hydrogen (Electrolysis)
9 Batt. Charge (24hrs)
10 Batt. Charge (Night)
11 FC Petrol (Partial Oxidation)
12 FC Biomethanol (Reformed)
13 FC Biomethanol (Internally Reformed)
14 FC Petrol (Reformed)
15 FC Petrol (Internally Reformed)
16 FC Bioethanol (Reformed)
17 FC Diesel (Partial Oxidation)
18 FC Bioethanol (Internally Reformed)
19 FC RME (Partial Oxidation)
20 FC Diesel (Reformed)
21 Propane (Partial Oxidation)
22 FC Diesel (Internally Reformed)
23 FC RME (Reformed)
24 FC Propane (Reformed)
25 FC RME (Internally Reformed)
26 FC Propane (Internally Reformed)
27 FC Methane (Partial Oxidation)
28 FC Methane (Reformed)
29 FC Methane (Int. Ref.)
30 FC H2 (Electrolysis)

Figure 8.4 Lifetime kg NMVOC/kW for Urban Buses

1-8 35% ICE, 9-10 70% Battery, 11-31 60% Fuel Cell



8.3.3.5 NITROGEN OXIDES

Compared with conventional fuels, increases in NO_x emissions occur with IC engines using bioethanol and RME, whilst the other alternate fuels produce comparable emissions (Figure 8.5).

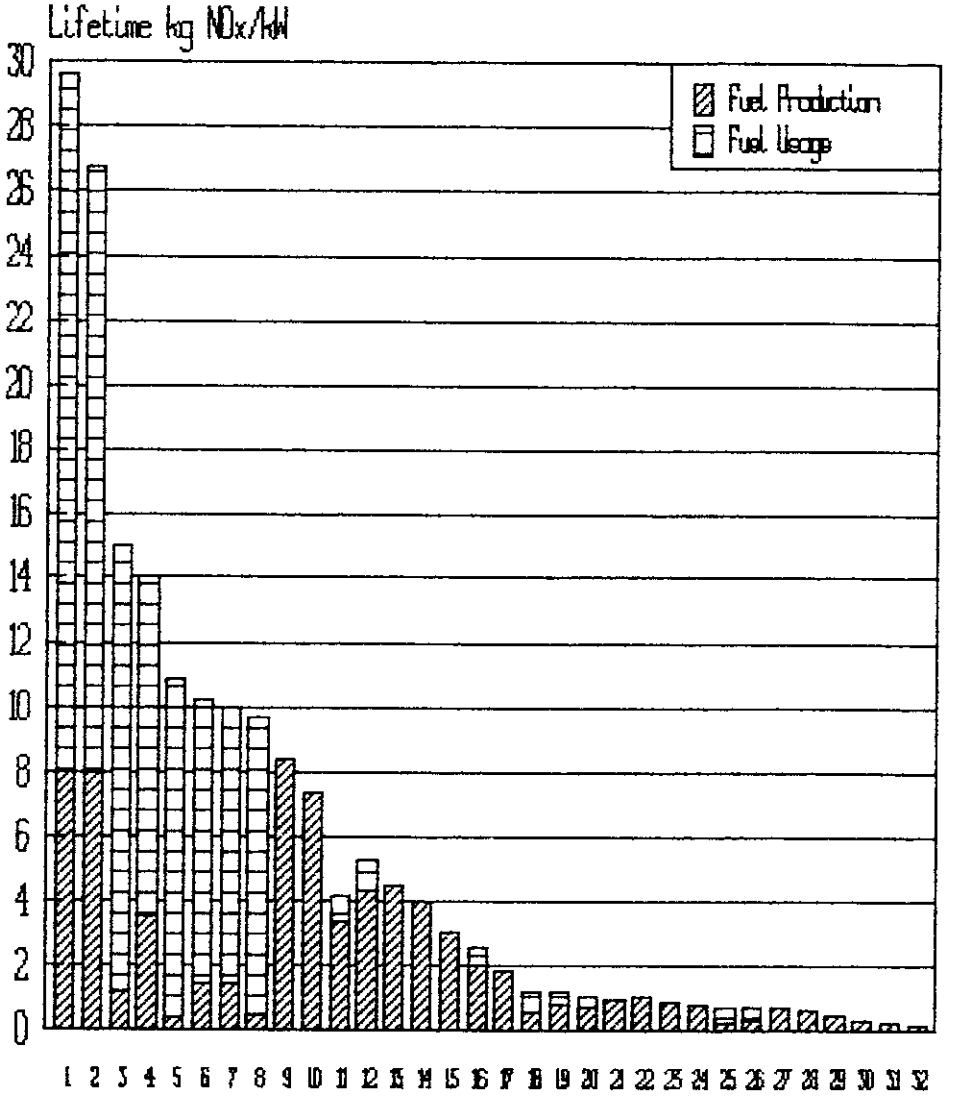
NOx emission are significantly reduced (below 150 g/kW, say) for fuel cell systems using diesel, propane, petrol, hydrogen, methanol and methane, with the lowest being for methane.

KEY TO FIGURE 8.5

1 ICE RME
2 ICE Bioethanol
3 ICE Diesel
4 ICE Biomethanol
5 ICE Methanol
6 ICE Propane
7 ICE Methane
8 ICE Petrol
9 Batt. Ch. (24 hrs)
10 Batt. Ch. (Night)
11 FC RME (Reformed)
12 FC Bioethanol (Reformed)
13 FC RME (Partial Oxidation)
14 FC Bioethanol (Internally Reformed)
15 FC RME (Int. Reformed)
16 FC Biomethanol (Reformed)
17 FC Biomethanol (Internally Reformed)
18 FC Diesel (Reformed)
19 FC Propane (Reformed)
20 FC Petrol (Reformed)
21 FC Petrol (Partial Oxidation)
22 FC Propane (Partial Oxidation)
23 FC H2 (Electrolysis)
24 FC Diesel (Partial Oxidation)
25 FC Methanol (Ref.)
26 FC Methane (Reformed)
27 FC Propane (Int. Reformed)
28 FC Petrol (Int. Reformed)
29 FC Diesel (Int. Reforming)
30 FC Methane (Partial Oxidation)
31 FC Methane (Internally Reformed)
32 FC Methanol (Int. Reformed)

Figure 8.5 Lifetime kg NOx/kW for Urban Buses

1-8 35% ICE, 9-10 70% Battery, 11-31 60% Fuel Cell

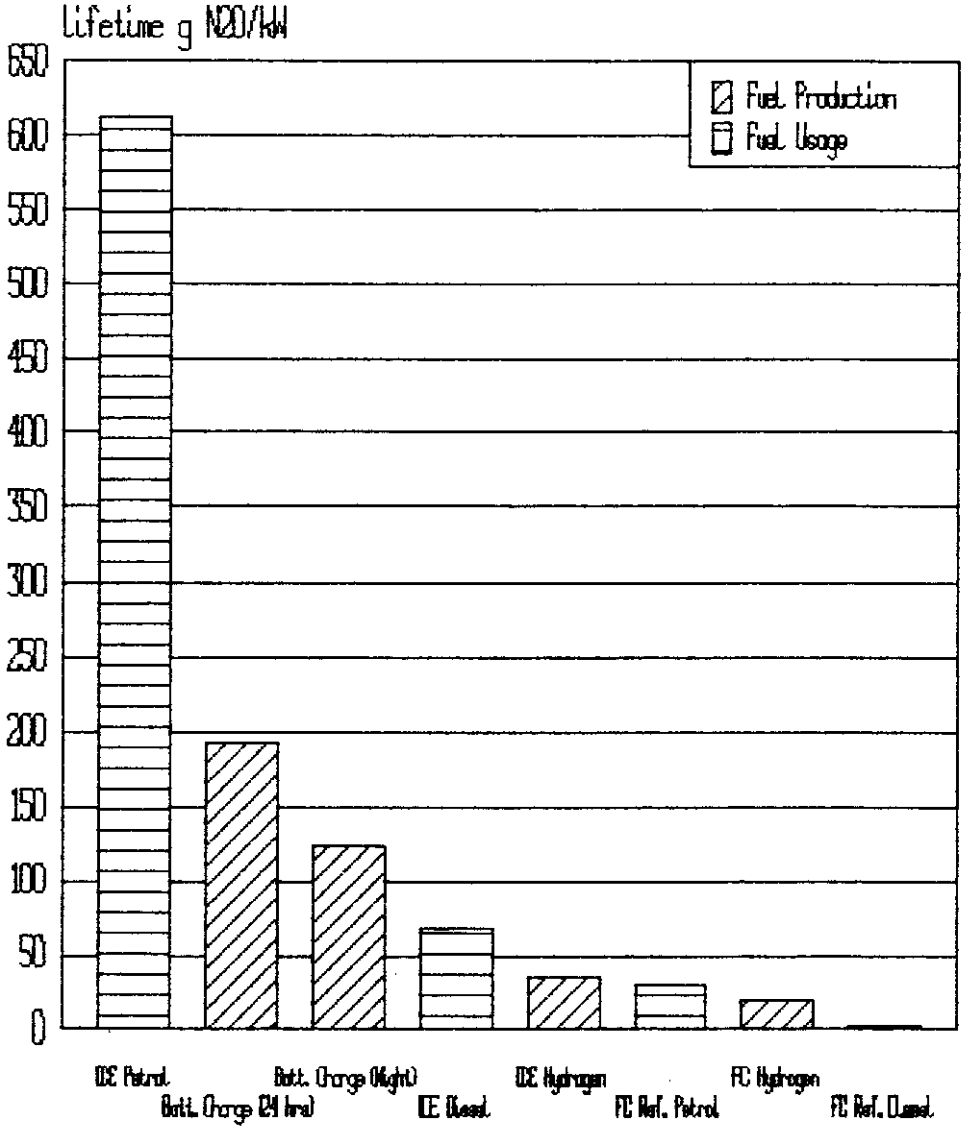


Nitrous oxide emissions are emitted from the production or use of only petrol, batteries, diesel and hydrogen (Figure 8.6). Of these, fuel cell systems using hydrogen and reformed diesel have the lowest values. Thus, it should be noticed that all the other fuels considered result in zero N_2O emissions.

KEY TO FIGURE 8.6

ICE Petrol (Use)
Batt. Charge (24hrs)
Batt. Charge (Night)
ICE Diesel (Use)
ICE Hydrogen (Electrolysis)
FC Petrol (Reformed) (Use)
FC Hydrogen (Electrolysis)
FC Diesel (Reformed) (Use)

Figure 8.6 Lifetime g Nitrous Oxide/kW for Urban Buses



8.3.3.7 SULPHUR DIOXIDE

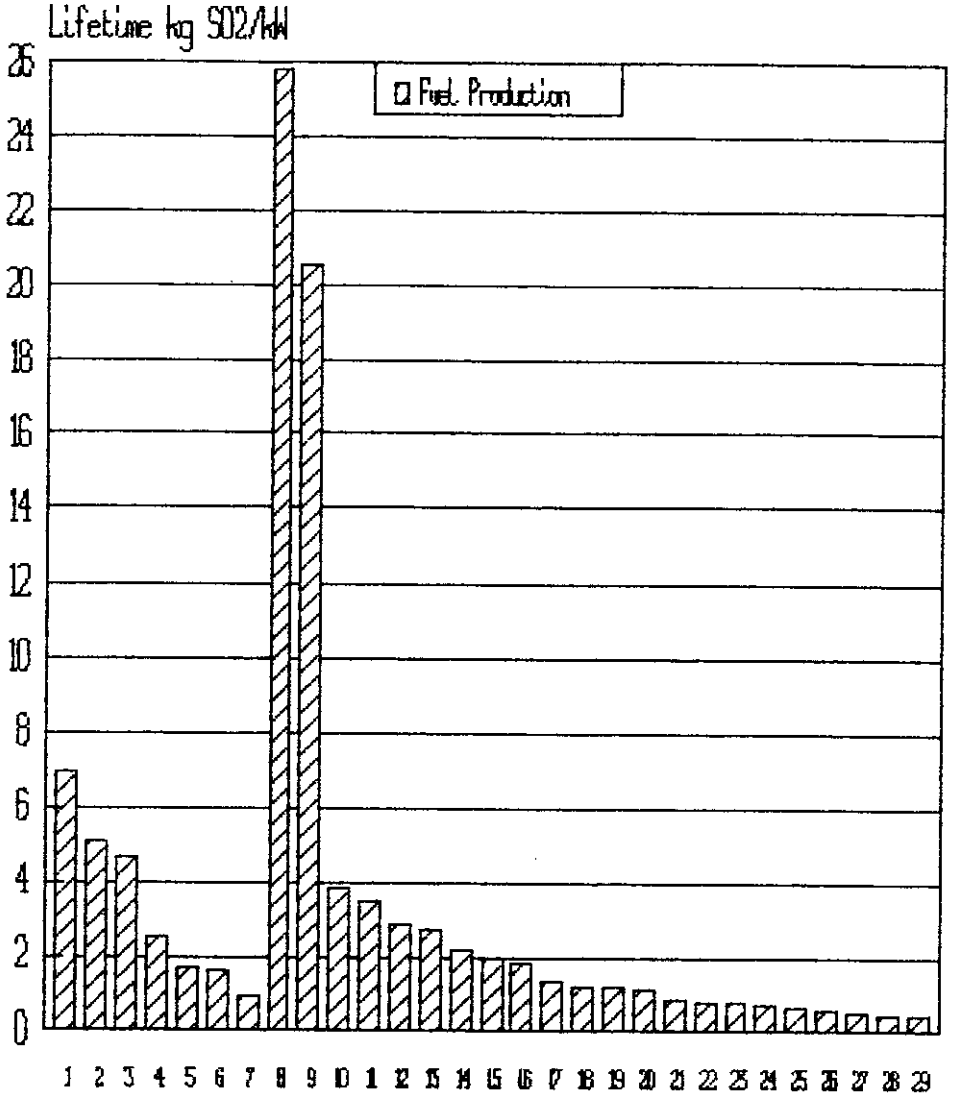
Emissions of sulphur dioxide are very high from power stations used for recharging battery vehicles and significantly reduced (below 1 kg/kW, say) from fuel cell systems using reformed diesel and using petrol, propane, methanol and methane, with the least amounts from methanol and methane (Figure 8.7).

KEY TO FIGURE 8.7

1 ICE Bioethanol
2 ICE RME
3 ICE Hydrogen (Electrolysis)
4 ICE Petrol
5 ICE Diesel
6 ICE ICE Propane
7 ICE Biomethanol
8 Batt. Charge (24 hrs)
9 Batt. Charge (Night)
10 FC Bioethanol (Ref.)
11 FC Bioethanol (Internally Reformed)
12 FC RME (Partial Oxidation)
13 FC H2 (Electrolysis)
14 FC RME (Reformed)
15 FC RME (Int. Reformed)
16 FC Petrol (Partial Oxidation)
17 FC Petrol (Reformed)
18 FC Petrol (Internally Reformed)
19 FC Diesel (Partial Oxidation)
20 FC Propane (Partial Oxidation0
21 FC Diesel (Reformed)
22 FC Propane (Reformed)
23 FC Diesel (Internally Reformed)
24 FC Propane (Internally Reformed)
25 FC Methane (Partial Oxidation)
26 FC Biomethanol (Reformed)
27 FC Methane (Reformed)
28 FC Biomethanol (Internally Reformed)
29 FC Methane (Internally Reformed)

Figure 8.7 Lifetime kg Sulphur Dioxide/kW for Urban Buses

1-7 35% ICE, 8-9 70% Battery, 10-29 60% Fuel Cell



8.3.3.8 PARTICULATE MATERIAL

Particulate material emissions are highest from IC engines, battery systems and fuel cell systems using biofuels (Figure 8.8).

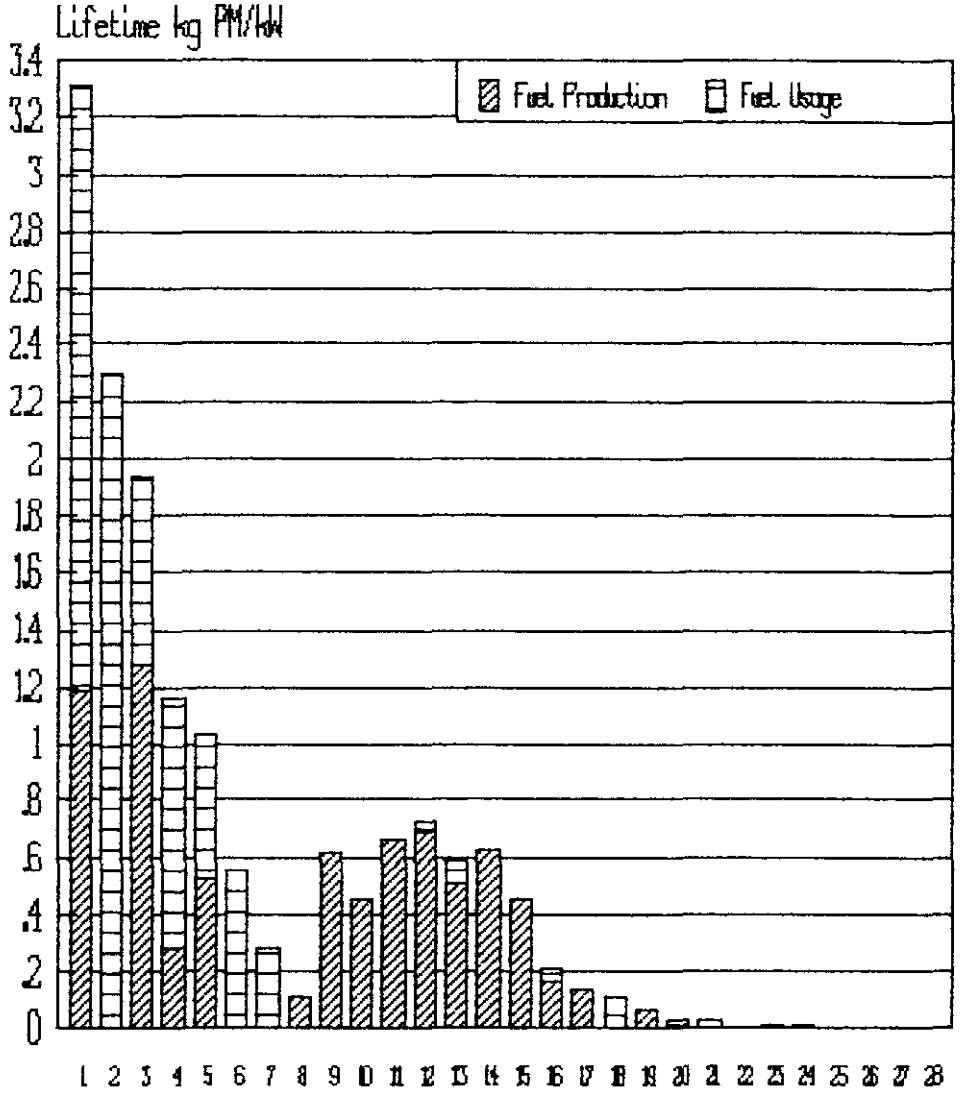
Significant reductions (below 0.1 kg/kW, say) are made from fuel cell systems using diesel, hydrogen, propane, petrol and reformed methane, with the least amounts from partially oxidised and internally reformed petrol and diesel.

KEY TO FIGURE 8.8

1 ICE RME
2 ICE Diesel
3 ICE Bioethanol
4 ICE Biomethanol
5 ICE Propane
6 ICE Petrol
7 ICE Methane
8 ICE Hydrogen (Electrolysis)
9 Battery Charge (24hrs)
10 Battery Charge (Night)
11 FC RME (Partial Oxidation)
12 FC Bioethanol (Reformed)
13 FC RME (Reformed)
14 FC Bioethanol (Internally Reformed)
15 FC RME (Int. Reformed)
16 FC Biomethanol (Reformed)
17 FC Biomethanol (Internally Reformed)
18 FC Diesel (Reformed)
19 FC H2 (Electrolysis)
20 FC Propane (Reformed)
21 FC Petrol (Reformed)
22 FC Methane (Reformed)
23 FC Propane (Partial Oxidation)
24 FC Propane (Internally Reformed)
25 FC Petrol (Partial Oxidation)
26 FC Diesel (Partial Oxidation)
27 FC Petrol (Internally Reformed)
28 FC Diesel (Int. Reformed)

Figure 8.8 Lifetime kg PM/kW for Urban Buses

1-8 35% ICE, 9-10 70% Battery, 11-28 60% Fuel Cell



8.3.3.9 FUELS

It has been assumed that the fossil and biofuels considered can be processed for use in fuel cells. These processes are steam reforming external to the fuel cell, internal reforming using high temperature fuel cells or partial oxidation for the hydrocarbon fuels. It is recognised that these processes need development for most of the fuels; steam reforming for fuel cells has been demonstrated for natural gas (eg, Itoh, 1989 and Sugimoto et al, 1992) and methanol (Toyota, 1997), and is being developed for diesel fuel. Partial oxidation is a possibility for hydrocarbon fuels and has been suggested as a possibility for an inboard fuel processor for fuel cell vehicles (Scarlett, 1997).

The biofuels bioethanol, biomethanol and RME require large areas of crops to provide fuel for road transport. Estimates of land requirements (ETSU, 1994 (a)) are as follows:

(a) 1 tonne of rapeseed oil produces 0.28 to 0.46 tonne of biodiesel or RME. Average yields in the UK are 3.2 t/ha for a winter crop and 2.2 t/ha for a summer crop. Using the figure for winter rape and an average of 0.37 t RME/t rapeseed gives 1.18 tRME/ha of land.

(b) 1 tonne of wheat produces 0.29 tonne of ethanol, and 1 tonne dry wood produces 0.13 to 0.19 tonne of ethanol. Average crop yields are 10 to 12 t/ha.

(c) 1 hectare of crop produces 120 GJ (about 4 tonnes) of methanol and 1 hectare produces 12 about tonnes of dry wood product. Thus, 1 tonne of dry wood produces 0.33 tonne of methanol.

For the estimate of land usage in (a) above, and if all set-aside land was used for rapeseed to produce RME, this would provide sufficient fuel for less than 7% of the potential market. If all set-aside land was used for wheat plus the diversion of all

wheat exports for ethanol production the estimate in (b) above would provide less than 10% of the potential market. In the case of methanol, if 20% of set-aside land was used for short rotation coppice, then less than 3% of the potential market could be supplied. Thus, biofuels could not achieve widespread use in the UK transport sector but could be used for market segments, such as small fleets of vehicles, (ETSU (1994(a)) and (Gover et al, 1996)

The introduction of fuel cells into the transport sector will need either a new fuel infrastructure for fuels such as hydrogen, natural gas (methane) LPG (propane) and alcohols, or could use the existing one for diesel fuel, petrol or possibly RME. However, natural gas and LPG have been introduced into some transport systems on a trial basis and electric motor systems are proven in many vehicles. **One main conclusion from the above results is that the most significant reductions in all emissions are obtained for fuel cell systems using diesel, propane, methane (except for methane losses during distribution) or hydrogen.** Because of this, also the above problems associated with biofuels and since reforming systems have not been developed for most fuels, the next chapter will concentrate on systems using hydrogen, steam reformed and partially oxidised methane and diesel. With the careful selection of fuel and operating system, it should be possible to introduce fuel cells into the transportation sector.

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9. INTRODUCTION OF FUEL CELLS IN THE TRANSPORT SECTOR

Successful commercialisation of fuel cells in transportation will require .... a willingness to pursue several technology pathways.
(S G Chalk et al, 1995).

9.1 INTRODUCTION

This chapter considers the methods by which fuel cell options could be introduced into the transport sector with a view to reducing pollution as well as road congestion. Recent opinion in the UK (Gover et al, 1996) indicates that although there are certain markets where alternative fuels could be envisaged, such as fleet operators, petrol and diesel will continue as the major fuels for the foreseeable future. For alternative fuels, they also suggest that fleet operators would be most viable, where fuel could be supplied through a central depot to vehicles operating in a limited geographical area. They also suggest that demand could be enhanced by legislation for improved urban air quality resulting in bus, freight and utility service operators in urban areas requiring low emission vehicles. From an economic aspect the most likely fuels for low emission IC engines are liquid petroleum gas (LPG) and compressed natural gas (CNG). The present thesis concentrates on fuel cells rather than alternative fuels for IC engines as a means of reducing urban air pollution.

As noted in Chapter 2, there is need to reduce the numbers of vehicles as well as to reduce vehicle pollution, and one solution for the easing of road congestion would be to reduce the numbers of private cars and increase and improve public transport. Vehicles with cleaner exhausts would reduce the level of traffic management needed for pollution control. Also, an enhancement to the environmental performance of public transport vehicles could assist in the promotion of their use. Commercial transport also would need to be rationalised and low pollution fuels introduced in this traffic sector. Finally, It is considered that the best way to reduce pollution from road

traffic exhaust would be to introduce electric vehicles.

This thesis has considered the use of battery and fuel cell powered electric vehicles. Fuel cell powered vehicles would require either:

(a) inboard fuel processing for hydrocarbon fuels or,

(b) the safe and acceptable (in terms of weight and volume) inboard storage of hydrogen.

It has already been noted that demonstrator vehicles using stored hydrogen have been successfully operated, but that a hydrogen fuel infrastructure would need to be put in place before such vehicles are commercially viable. Also, battery systems, although with limited performance in terms of range and possibly acceleration, are currently available. Both systems are more expensive to build than IC engines which have a long history of reliable and acceptable usage in many applications. However, it is noted that batteries are less expensive than fuel cells, and likely to remain so even after fuel cells have been suitably developed. Thus, one solution, proposed by the author in Chapter 2, is to provide zero emission vehicles using minimum emission energy sources would be to introduce battery driven vehicles recharged, mainly overnight, from fuel cell power generation stations. Initially, this would be ideal for vehicle fleets and urban or city public transport systems, considered later in this chapter, and could be a Combined Heat and Power (CHP) system for waste heat to be used locally and daytime power either used locally or fed into the national grid. To achieve the same for private cars, either the pollution from central power stations needs to be significantly reduced or, replaced by cleaner electrical generating systems (see Chapter 7).

However, as well as this proposal, consideration will now be given to a range of options for introducing fuel cells to the transport sector, with emphasis on city and urban buses; note that these could be applied to other forms of land public transport, other fleet operators and to private cars.

The ideal solution to minimise pollution from transport is to provide a low pollution manufacturing and delivery infrastructure to supply hydrogen for storage on fuel cell powered vehicles. However, this thesis has concentrated on the use of existing fuels as a first step, and there are a number of ways in which fuel cells could be introduced to the transport sector using fossil fuels:

(a) supply an existing liquid fuel, such as diesel, which could be processed on board vehicles to produce a mixture of hydrogen and carbon dioxide for use with air in fuel cells.

(b) supply an existing liquid fuel, such as diesel, to main depots where it is processed to produce gaseous or liquid hydrogen for transfer to fuel cell vehicles.

(c) supply a new fuel, such as an alcohol, CNG or LPG, for processing on board fuel cell vehicles, as in (a), above.

(d) supply a new fuel, such as an alcohol, CNG or LPG, to main depots for processing to hydrogen as in (b), above.

(e) as proposed in section 9.1 above, generate electrical power, for recharging battery driven vehicles, using fuel cell power generators using one of a number of possible processed fuels. The generators could be dedicated to particular areas.

(f) generate electrical power for electrical transport vehicles where the power is transferred from overhead cables, such as for trams or railways.

These options, (a) to (f) above, are considered in the following sections.

9.2 SYSTEMS WITH INBOARD FUEL PROCESSING

At the present time, the development of inboard steam reformers are underway for methanol as a fuel and the proposed development of other compact inboard processors for hydrocarbon fuels has been reported (Scarlett, 1997). However, such systems are relatively complicated, and require a new fuel infrastructure for new fuels, such as methanol, CNG or LPG, and a longer period of development for hydrocarbon fuels than for methanol. Additionally, although the reduction in most pollutants is considerable when using reformed methanol, the reduction in carbon dioxide is marginal compared with IC engines using petrol or diesel and the total amounts of carbon monoxide and NMVOC are relatively high compared with other fuels (chapter 7, above).

The results in Chapter 7 indicate that no one fuel has the lowest emission values for all pollutants. However, good compromises for least overall emissions are reformed methanol, propane, diesel and (except for losses during distribution) methane.

Potentially, the best inboard fuel reforming process would be to use high temperature fuel cells and internal reforming. Solid oxide fuel cells offer the best potential option in terms of power to weight ratio (chapter 3), but further development is required.

9.3 CENTRAL FUEL PROCESSING

The concept of providing fuel processing at fuel depots requires less development than for compact systems on board vehicles. Large steam reformers for natural gas and methanol are already available and processors could be developed for other hydrocarbons. However, this requires the added difficulty of removing the carbon dioxide from the reformate gas and compressing or liquefying the hydrogen gas, as well storing either gaseous or liquid hydrogen inboard vehicles.

9.4 FUEL CELL POWER GENERATION FOR RECHARGING BATTERY VEHICLES

9.4.1 INTRODUCTION

Since their successful development, employment in space applications and demonstration in other fields, the commercialisation of fuel cells for central electrical power generation and to power electric transport vehicles has been slow. To reduce energy used in, and pollution from, road transport, there is a need to introduce high efficient systems such as fuel cells in the transport sector as soon as possible. Also, relatively small fuel cell power stations (up to 20 MW) could be more easily built at present than larger one units (100s MW) because of the currently available manufacturing facilities.

Consequently, the concept of generating electrical power using fuel cells for recharging zero emission battery driven vehicles might be an ideal first step in introducing fuel cell technology to road transport. Fuel cell electrical power generation using natural gas and air is already a proven option up to at least 10 MW, see chapter 3, above, and could be developed for other hydrocarbons; also, they could be CHP systems to make use of the waste heat. Although this has no benefits above those that could be realised by using fuel cells to generate electricity for the national grid, there may be technological and economic reasons for such a proposal. It would also form a demonstrated link between transport and fuel cells which could be achieved with present day systems. Other fuels could be introduced, particularly when high temperature fuel cells with internal or closely integrated reforming of fuels are developed. The reduction in pollution for fuel cell systems and a variety of fuels has already been considered in chapters 7 and 8. When problems of fuel production and reformation are taken into account, these results show that natural gas and diesel fuel give the least overall pollution, apart from gas losses during acquisition and distribution, coupled with the least development.

9.4.2 POSSIBLE POLICY PROBLEMS

The above proposal raises several questions which need to be considered. Firstly, the issue of a clear split between power generation as a utility and for electric vehicles. Secondly, the issue of a choice between battery and fuel cell powered electric vehicles. Thirdly, the question of why the generation of power for recharging battery vehicles should be different from that for the national grid? Fourthly, the types of fuel cell currently being used in power generation demonstrators are different to those in electric vehicle demonstrators.

The proposed power system could be located anywhere that is convenient for such issues as fuel supply and convenience to a power generating authority. However, there is a case for it to be local to a public transport system, such as city buses, and dedicated to recharging battery vehicles overnight:

(a) if the power is generated by electric power companies there would be no incentive to develop fuel cell vehicles to replace the battery vehicles when an appropriate fuel infrastructure exists,

(b) fuel cell systems are modular, and basic stacks of a few hundred kilowatts could be added as the fleet of battery vehicles grows,

(c) the proposed system could possibly use an existing transport fuel, such as diesel, to gradually introduce electric vehicles alongside existing public transport using the same fuel,

(d) there is a clear need to develop pollution free vehicles, and in terms of overall energy efficiency fuel cells would be an improvement over batteries,

(e) the proposal offers the opportunity to introduce fuel cells into the transport

sector earlier than other strategies which require a new fuel infrastructure, and possibly at a lower cost,

(f) electricity could be used locally during the day or, with the appropriate control equipment, sold to the national grid.

(g) the proposed system, if CHP, could make use of the waste heat locally for applications such as local council buildings and hospitals,

The issue of different types of fuel cell for different applications is an important one, and the above proposal could lead to one application and type of cell being preferentially developed at the expense of another. It would probably be easier initially to build a PAFC power station because these have been used in stationary demonstrators ranging from 40 kW to over 10 MW. On the other hand, the most successful mobile demonstrators have used either AFCs or PEMFCs, the latter appearing to be favourite. However, PAFCs have been proposed for large buses and in any case, the provision of more demonstrators would increase the prospects for fuel cell systems to be competitive with conventional systems. Also, as more and more demonstrators come on line this would reduce manufacturing costs and enhance the development of fuel cells in general, and could enhance their development for mobile systems. The first of such systems would be an ideal candidate for development grants from governments and fuel cell manufacturers who might wish to see demonstrators in a number of fields. Future development will allow the use of high temperature fuel cells with internal or integrated fuel reforming.

Alternatively, the use of renewable resources could be considered. Potential renewable resources are hydro-electric, solar, wind, tidal and geothermal power. Each of these would involve the use of land or tidal estuaries, and one way to introduce them is to build some of each on an opportunity basis, as and when required, each type being dependent upon location. The introduction of any of these systems as dedicated power supplies for public transport would depend critically upon location, and is not

practicable for most urban and city buses. For instance, see section 6.5.1 in chapter 6 for spacing and consequent land requirements for wind turbines, section 8.3.3.9 in chapter 8 for the land requirements for growing crops to produce biofuels, and paragraph 9.4.5 below for a detailed analysis.

9.4.3 EMISSIONS

As already stated, the results in chapter 7 for fuel cell systems also apply to electrical power generation stations, and hence comparisons can be made between the proposed system and other transport systems. By choosing a particular efficiency for the fuel cell power station, the amounts of emissions can be found from the results in chapter 7. The efficiencies of fuel cell power stations are different for different types of fuel cell, and could vary between 0.45 to 0.5 for PAFCs to 0.55 to 0.65 for PEMFCs. In the first instance, it would be easier to build a PAFC power station since these have already been proven in large demonstrators.

Total emissions (for fuel production plus usage), using steam reformed and partially oxidised (plus a CO steam shift reaction) methane or natural gas and diesel fuel, for the fuel cell efficiency range of 0.45 to 0.65 are calculated for a battery efficiency of 0.7 and a charging efficiency of 0.9:

Mass of pollutant/kWh for recharging battery system

= (Mass of pollutant/kWh of electrical energy generated)
/(0.9)/(0.7) [1].

A comparison of emissions from fuel cell and IC engine vehicles and from power stations used to recharge battery vehicles was made in Chapter 7, and the results for fuel cells are applicable to power generators. For fuel cell power generators used to recharge battery vehicles, the comparison must be made with other sources of electricity generation.

The emissions from fuel cell power generators, calculated from equation [1], above, are shown in Table A.20 in Appendix A. The emissions for charging batteries from the current mix of power stations and a battery efficiency range of 0.6 to 0.8 are included for comparison.

9.4.4 DISCUSSION OF RESULTS

Carbon dioxide emissions for most of the fuel cell systems are significantly less than for conventional power stations, with methane having the lowest values, representing a 31% to 49% improvement (for a 60% efficient fuel cell), depending on the battery efficiency. CO_2 emissions for fuel cells using partially oxidised diesel fuel are comparable with, or higher than, those from batteries.

Carbon monoxide emissions are highest for fuel cell systems using externally reformed diesel fuel; other fuel cell systems are significantly less (by 60% to 90%) than for conventional power stations.

Nitrogen oxide (NOx) emissions for the fuel cell systems are very much lower (by 70% to 80%) than for conventional power stations, with methane again having lower values than diesel fuel.

Emissions of non methane volatile organic compounds (NMVOC) for conventional power stations are considerably less than for the fuel cell systems. However, NMVOC emissions using methane are less than those for diesel fuel. This pollutant is worse for fuel cells than for conventional power generators. Most of the NMVOCs comes from the oil fuel transport and refining process, see Table 7.2 in Chapter 7.

Methane emissions for fuel cell systems using methane as a fuel are comparable with those for conventional power stations, mainly because of losses attributed to filling stations, Table 7.4 in Chapter 7. Methane emissions for fuel cell systems using diesel fuel are significantly less (by 90% to 93%) than for methane or conventional power

stations.

Sulphur dioxide emissions are high for conventional power stations and significantly less (by 93%) for the fuel cell systems.

Emissions of particulate material for the fuel cell systems are significantly less (by 90% to 98%) than for conventional power stations, with those for fuel cell systems using methane having the lowest values. PM emissions for fuel cells using externally reformed diesel fuel are higher than for methane mainly due to the emission from the fuel burner to provide the heat of reformation. This could be reduced by suitable treatment of the burner exhaust gases.

The results indicate that the use of fuel cell power generation stations to recharge battery vehicles would significantly reduce most emissions when compared with conventional power stations. It has been pointed out in section 9.1 above, that the introduction of fuel cell driven vehicles with either in board fuel reforming or hydrogen storage requires either development of inboard reformers or a hydrogen fuel infrastructure. Thus, the provision of dedicated fuel cell power using an existing fuel to recharge battery driven buses, particularly for urban and city use, is considered to be an effective way of introducing fuel cells to the transport sector. Both natural gas and diesel fuel have suitable fuel supply infrastructures and a natural gas reformer could be built without development costs.

9.4.5 COMPARISONS WITH OTHER SYSTEMS

Other low pollution systems could be used to produce electrical energy to recharge fleets of battery driven vehicles, such as city buses. These are:

(a) biofuels, processed from crops to provide the fuel for the fuel cell power station.

(b) Renewable energy resources.

Biofuels could be used to provide the fuel for the fuel cell power station when the net carbon dioxide emissions would be those due to the fuel manufacturing processes. The amount emitted from the power station would be cancelled by that absorbed by the crops during their growing period. However, it has been shown in chapter 7 that other pollutants are greater for biofuels when compared with natural gas or diesel.

For RME, the amount of land required is 0.85 hectares/tonne of fuel produced (ETSU, 1994a), and from Table A1 in Appendix A, the RME fuel consumption for a 50% fuel cell is 0.178 kg/kWh or 0.178 tonne/MWh. Thus, the amount of land required to provide RME for a power station using 50% efficient fuel cells is about 0.15 hectare/MWh of output energy.

A typical inner city bus fleet of one hundred 130 kW battery driven buses operating for 12 hours per day requires 156 MWh of recharging energy. For 50% efficient fuel cells, 70% efficient batteries and a 90% efficient charging system, this gives a fuel requirement of about 44 tonnes for each overnight recharge, or 16.1 kt/year requiring about 13,700 hectares (33,900 acres) of land for an annual crop of rapeseed. This would need to be located within a practicable distance of the fuel cell power station and hence near the city which is served by the buses.

As discussed in chapter 6, the emissions from renewable resources would be very low but would require land space. For wind generated electrical power the land requirement depends upon the turbine blade size and the amount of wind, and varies from 4.7 to 16 hectares/MW (Johansson et al, 1993). Thus, the land requirement for above fleet of minibuses, with 70% efficient batteries and for 90% efficient charging, varies between 5.3 and 1.6 hectares (13.1 to 4.0 acres). This would be feasible only in restricted areas, based on land available and average wind velocities, and would need to be near the city served by the buses or sold to the national grid.

9.5 CENTRAL FUEL CELL POWER GENERATION FOR SUPPLYING ELECTRIC VEHICLES VIA OVERHEAD CABLES OR CONDUCTOR RAILS

Similar to that considered above for recharging battery vehicles, the concept of generating electrical power using fuel cells for providing power to electric vehicles via overhead cables or conductor rails could be an another first step in introducing fuel cell technology to transport. This system could apply to either rail or tram vehicles, but would require dc to ac conversion for alternating current systems. Emissions from fuel cell power systems in terms of mass of pollutant per kWh of generated energy are calculated in chapter 7 for a range of fuel cell efficiency. Assuming an efficiency for the electric vehicle drive system, the emissions for different vehicles are calculated as follows:

Mass of pollutant/kWh for electric vehicle
= (Mass of pollutant/kWh of electrical energy generated)
/drive efficiency [2],

neglecting the efficiency of power transmission to the vehicle, which would be the same whatever the generation method.

9.5.1 RESULTS

Results for fuel cell efficiencies between 0.45 and 0.65 and an electric drive efficiency of 0.85 are shown in Table A.21 in Appendix A. Emissions for the current mix of power stations and vehicle drive efficiency between 0.75 and 0.9 are included for comparison. These results follow the same trends as those for power stations used to recharge battery systems (section 9.4) above, but the differences between those for conventional and fuel cell power stations are less marked because of the difference in efficiencies used (ie for electric drives rather than batteries). The remarks in the final paragraph at the end of section 9.4.1 above, apply also to the results in this section.

9.6 COMBINED ELECTRIC RAIL LOCOMOTIVES AND ROAD VEHICLES

In the previous two sections, electric power stations using fuel cell technology have been proposed for recharging battery driven road vehicles and for electric vehicles supplied via overhead cables or conductor rails. These could be combined to produce a clean commercial vehicle transport system consisting of battery driven container delivery vehicles carried inboard electrically driven trains, where they are recharged during long journeys.

Such a system would be preferable to the current European rail system which uses the channel tunnel to transport heavy goods vehicles. It could use goods containers which are transported by ICE or battery driven road vehicles to rail depots where they are than transferred to the battery driven container vehicles for transport to depots near the final destinations of the goods carried. During this transport phase the battery vehicles are recharged via the rail transport electric supply system, and deliveries are thus made locally using pollution free vehicles. Such a system would help to alleviate the current problem of heavy European goods vehicles in the UK as well as being completely powered from low polluting fuel cell generators.

9.7 DISCUSSION

This chapter has addressed the problem of introducing a new technology into the transport sector, which has used a tried and reliable power source for nearly a century. The development of the internal combustion engine has reached a stage of development and acceptability where a competitor would probably need to be supported by legislation for low pollution vehicles. In addition, considerable development is needed before fuel cell systems for use in vehicles are competitive. Although several prototype systems have been, and are being, successfully demonstrated, these carry compressed or liquid hydrogen or methanol, which require considerable development for a fuel infrastructure before being competitive with conventional fossil fuels. Thus, legislation

for low pollution vehicles is probably required to support the development of a new fuel infrastructure. Also, as shown in Section 7.6 in chapter 7, fuel cells produce relatively large amount of water (nine kg of water per kg of hydrogen used) which, at a fuel cell efficiency of 60% and corresponding hydrogen consumption of 0.05 kg/kWh, amounts to 0.45 kg or litres per kWh. For a typical minibus this totals 45 litres/h (9.89 gallons/h) or 360 litres (79.2 gallons) over an eight hour operating period or, for a typical single deck bus, 90 litres/h (19.8 gallons/h) or 720 litres (185.3 gallons) over an eight hour period. Thus, although the fuel cell waste water is a harmless product, if a large number of fuel cell powered vehicles used pure hydrogen, it might have to be stored inboard, particularly in cities and urban areas, which could impose difficulties in vehicle design. It should be noted however, that a 35% efficient ICE using diesel fuel produces water vapour at the rate of 0.33 kg/kWh.

If conventional fuels are processed to produce a hydrogen rich mixture suitable as a fuel for fuel cells, as in the case of steam reforming, the water could be provided from the fuel cell waste product. This still leaves considerable excess water in some cases (Table 7.18 in chapter 7). However, currently, this is probably only feasible for inboard systems in the near term for easily reformed fuels such as methanol or natural gas. Although work is proceeding on the development of portable systems for other fossil fuels, particularly diesel fuel, considerable development is still required. The future development of high temperature fuel cells, such as the solid oxide type, which could provide the heat of reformation for integrated or internal fuel reforming, could be a solution for some vehicle systems (Steele, 1996) depending upon the fuel cell warm-up time required.

In the mean time, possible ways of introducing fuel cells in the near term which would enhance both their development and produce zero emission vehicles is to provide fuel cell electric power generation:

(a) to recharge battery driven road vehicles as proposed in section 9.4 above,

(b) to provide energy for vehicles using overhead cables or electric rails as proposed in sections 9.5 above,

(c) to provide energy for a combination of (a) and (b) as proposed in section 9.6 above.

Any of these proposals probably could be achieved in a lesser time scale than would be required for developing fuel cell driven vehicles; fuel cell power generation systems using natural gas have been successfully demonstrated at all power levels up to tens of MW using existing technology for gas reforming (Chapters 3 and 5).

In the near term, the installation of a dedicated demonstrator plant to recharge a fleet of battery driven vehicles, such as for urban or city public transport, appears to be a good option. This also might attract Government, European or Industrial funding support.

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10. CONCLUSIONS

10.1 SUMMARY

The main subject of this thesis has been the study of the potential for fuel cells in the transportation sector to reduce harmful emissions into the atmosphere. To this end, calculations have been made of fuel consumption, energy and emissions due to both fuel production and usage, for a range of fuels and fuel cell efficiency, and the results compared with those for internal combustion engines. However, although the reduction of emissions is an important issue, it is recognised that there is also a need to reduce traffic congestion. Thus, it is considered that any new low pollution system should first be applied to public transport systems, which need to provide an improved service if the number of private vehicles is to be reduced. Also, comparisons are made with battery driven vehicles recharged using the current mix of power stations. The results have been used to calculate lifetime emissions for systems using 60% efficient fuel cells, with particular reference to public transport. Finally, various ways of introducing fuel cells to the transport sector have been considered.

10.2 MAIN FINDINGS

10.2.1 ATMOSPHERIC POLLUTION

For many years, the majority of scientific opinion has maintained that the burning of fossil fuels has influenced climate by increasing pollutants in the atmosphere which contribute to global warming and, more recently, that some of these pollutants are presenting an increasing risk to health. To date, even though some recent scientific opinion calls for the analysis of further data and that different methods give different results, the overriding scientific consensus is that global warming will continue unless measures are taken to moderate the contributing factors from human activities. The

emissions from IC engines in the transport sector are thought to be a major contributor to global warming and, if allowed to continue, could have a harmful effect on health and climate.

Fuel cells are considered to be a suitable candidate to replace IC engines, the proton exchange membrane (PEMFC) type being the most suitable for commercial development in the short term, with possibly high temperture types following.

10.2.2 FUELS FOR FUEL CELLS

Fossil fuels and alcohols have been considered in terms of their processing (steam reforming or partial oxidation) to produce a hydrogen rich gas suitable for use in fuels cells. Consequently, methanol, ethanol, methane, and natural gas are considered to be suitable, with diesel fuel a possibility. However, other fuels, namely petroleum, RME and propane are included in the overall analysis, since suitable processing systems might be developed in future. Ammonia and chemical hydrides have been considered but discarded because (a) development is required for processing ammonia which is also highly toxic, and (b) hydrides need to be stored and processed as solids in relatively large quantities, are expensive and highly reactive. Hydrogen, for which storage methods suitable for transport systems are under development, is the cleanest fuel but its widespread use depends upon development of a suitable infrastructure for production and delivery.

10.2.3 FUEL PROCESSING FOR FUEL CELLS

Systems for processing hydrocarbon, alcohol, and methyl ester fuels might be developed for inboard use on vehicles, but if compressed hydrogen gas or liquefied hydrogen becomes acceptable then fuel processing could be centralised and the hydrogen delivered to main outlet stations. Endothermic fuel processes which require more than the waste heat from the fuel cell for operation to produce a hydrogen rich gas, could be activated by burning a small amount of fuel; steam for reforming could

be provided from the waste water from the fuel cell. Residual constituents of carbon monoxide and fuel carried over from the process reactions need to be removed, such as by the use of a selective catalytic oxidiser. High temperature fuel cells, operating at about 1,000^{o}C could be designed to internally reform fuels using the waste water from the fuel cell to provide steam.

10.2.4 ENERGY AND EMISSIONS

Calculations of energy and emissions from the production and use of fuels show that, although in general fuel cells have lower energy and fuel consumption than IC engines because of their higher efficiency, some fuels produce nearly comparable amounts of atmospheric pollutants. In particular, partial oxidation of fuels results in more carbon dioxide than steam reforming, and the alcohols produce more than the fossil fuels, with significantly less amounts of carbon dioxide for reformed methane, and in particular, hydrogen. Internal reforming using high temperature fuel cells, such as the solid oxide type, produces the least amount for each of the alcohol or hydrocarbon fuels. If the CO_2 emissions emitted during the use of biofuels is offset against those absorbed during the growing period of the feedstock crops, then these fuels produce amounts comparable with hydrogen as a fuel. However, this offsetting is appropriate over a relatively long time scale. Conclusions relating to the other pollutants are given in the next section on total lifetime emissions for urban buses, which follow the same overall trends.

10.2.5 THROUGH LIFE EMISSIONS

Lifetime total (fuel production or battery charging plus usage) emission calculations for urban buses using IC engines, fuel cells or batteries have been made. Assumptions are 35% efficient IC engines, 60% efficient fuel cells and 70% efficient batteries, and the results show that emissions are significantly reduced for some fuel cell systems, depending upon the fuel and fuel processing used. These results could be applied in general terms to other transport systems. General comments on the results (Table 1 in

the Overview gives an overall summary) are as follows:

(a) Carbon dioxide emissions for fuel cells using hydrogen produced by electrolysis are reduced by an order of magnitude when compared with IC engines using fossil fuels. Compared with IC engines, CO_2 is reduced by about 75% for the next best fuel, methane or natural gas. The emissions from fuel cell systems using reformed alcohols, or fossil fuels are reduced to about 50% of those for IC engines. The remarks on biofuels above also apply to these results. CO_2 emissions for recharging battery driven vehicles using the current mix of power stations are comparable with those for IC engines. These emissions are reduced very significantly for recharging batteries using renewable resources but, because of the land requirements, are probably applicable only in special circumstances or for specific applications such as fleets of vehicles.

(b) Except for externally reformed diesel and petrol, and the biofuels RME and bioethanol, carbon monoxide emissions are significantly reduced for batteries and fuel cells when compared with IC engines. The lowest, (an almost insignificant amount of less than 0.1g CO/kW of vehicle power) are for hydrogen from electrolysis, internally reformed petrol, methanol, diesel or methane, or partially oxidised methane.

(c) Emissions of methane are greatest for IC engines and fuel cells when this gas or methanol (where methanol is produced from natural gas) are used as a fuel, mainly due to losses occurring during the gas distribution phase. However, those for fuel cells are less than one third of those for IC engines, and about one half of those for battery charging. Those for recharging batteries using the current mix of power stations are significantly greater than from IC engines using conventional fossil fuels. Significant reductions are obtained for fuel cells using biomethanol, and substantial reductions (about 5 times higher) for hydrogen from electrolysis and reformed petrol and diesel. Almost zero methane emissions are found for fuel cells using ethanol, bioethanol or RME.

(d) NMVOC emissions are lowest for fuel cells using hydrogen produced by electrolysis and battery charging. NMVOC emissions for fuel cells using bioethanol, biomethanol, petrol and diesel are comparable with the range of results for IC engines. Significant reductions are obtained for fuel cells using reformed diesel, RME, propane or methane.

(e) When compared with other fuels, emissions of nitrogen oxides (NOx) are increased for IC engines using bioethanol or RME. Those for battery charging using the current mix of power stations are comparable with IC engines using methanol, petrol or propane. Significant reductions of about one order of magnitude less than the best result for IC engines (methane) are obtained for fuel cells using reformed or partially oxidised diesel, propane, petrol or methanol, or hydrogen from electrolysis. Further reductions are found for partially oxidised or internally reformed methane and internally reformed diesel or methanol.

(f) Nitrous oxide (N_2O) emissions are found only for petrol or diesel fuelled IC engines, battery charging and fuel cells using hydrogen or reformed petrol or diesel. That for reformed diesel is significantly less than for the other fuels.

(g) Compared with the other systems, the sulphur dioxide emissions are much higher for battery charging using the current mix of power stations; this could be reduced by suitable control of the exhaust gases. When compared with the other fuels SO_2 emissions are higher for IC engines using ethanol and RME. Results for most fuel systems with fuel cells are comparable with the range for IC engines using fossil fuels. However, significant reductions are obtained for propane, diesel, methanol or methane; the least amount being for methane.

(h) Emissions of particulate material are highest for IC engines using RME, diesel or bioethanol; those for biomethanol or propane are comparable, and the lowest values are for petrol or methane the latter being the lowest. Those for

battery charging and fuel cells using the biofuels are comparable with that for IC engines using petrol. Significant reductions are found for fuel cells using hydrogen from electrolysis or partially oxidised or reformed fossil fuels. Zero PM emissions are found for partially oxidised or internally reformed methane.

No single fuel used in fuel cell systems has been found to reduce all the above emissions to insignificant amounts, but hydrogen, propane, methane (except for methane losses during distribution) or diesel have distinct advantages over the others. In order to achieve a significant improvement in overall emissions there is a need to select the type of fuel cell and related fuel processing system.

10.2.6 INTRODUCTION OF FUEL CELLS INTO THE TRANSPORT SECTOR

The introduction of fuel cells into the transport sector will need a new fuel infrastructure for delivery to vehicles for some of the potential fuels considered, namely hydrogen, natural gas (methane), LPG, (propane) and alcohols. Other fuels considered, namely diesel, petrol and possibly RME (rape methyl ester), could use the existing fuel infrastructure. Also, other issues, such as the ease with which fuels can be processed, either by partial oxidation or reforming, for use with fuel cells, and the development required to produce competitive fuel cell systems, have been considered. Consequently, in the near term, it is considered that it would be difficult to introduce fuel cells into vehicles on a commercial basis.

In the longer term, systems are being developed for fuel cell vehicles using hydrogen or inboard processing of hydrocarbon fuels or alcohols. For liquid fuels, most advantages in terms of overall emissions would be obtained by using hydrocarbon fuels, particularly diesel with internal reforming, which could be used in IC engines whilst fuel cells are being introduced. For gaseous fuels, hydrogen has most advantages in term of overall emissions with natural gas (methane) being a good compromise which could be employed in IC engines whilst fuel cells are being introduced. However, systems using pure hydrogen would result in relatively large

amounts of waste water from fuel cells. This presents no problem during the introduction of the first fuel cell driven vehicles but, as numbers increase, particularly in cities, it may be necessary to store this inboard thus imposing restraints on vehicle design.

Other ways of introducing fuel cells in the transport the sector, which would have the advantage of enhancing competitive fuel cell development and reduce energy and overall emissions, are to use fuel cell power generation stations to:

(a) charge fleets of battery driven vehicles, particularly for city and urban buses,

(b) provide energy for electric vehicles via overhead cables or electric rails,

(c) provide energy for a combination of electric vehicles powered by via overhead cables or electric rails and battery driven commercial delivery road vehicles carried inboard over large distances whilst their batteries are charged.

Reasons for siting such a system near to an urban public transport and the initial consideration of other strategic issues have been given in section 9.4.2 of Chapter 9.

The installation of the latter system on main line trains and in the channel tunnel would help to ease the problem of large commercial vehicles in the UK, particularly from mainland Europe.

10.3 FUTURE WORK AND TRENDS

Effort is being made by European governments to reduce global warming by reducing emissions from transport. This thesis has shown that certain developments in fuel cells and the relevant fuel technology could enhance this policy. In particular, if fuel cells are introduced using inboard fuel processing, then the use of diesel fuel or natural gas could be advantageous since fuel cell vehicles could then use the same fuel

infrastructure as existing vehicles. Most benefit could be obtained by using internal or integrated reforming of fuels using high temperature fuel cells. Currently, there are both cost and development barriers in applying fuel cells, but the development of a system which could use any of a number of fuels currently being used in the transport sector would be advantageous. This could be provided on a vehicle by the development of a partial oxidising unit which combines a carbon monoxide shift reaction to convert the CO to CO_2. If the future development of low pollution vehicles followed this trend then fossil fuels in fuel cell driven vehicles could be used alongside conventional vehicles. Such developments require further study.

The proposals made earlier in chapter 9 and summarised above, to use fuel cell electrical generating stations in a variety of ways to provide energy for electric vehicles, need to be studied in detail. A first system, which requires the least development, could be a fuel cell power station using reformed natural gas to provide energy to charge a fleet of battery driven city buses. However, consideration needs to be given to how this might affect the development of compact fuel cells for transport applications. It could adversely affect their development in the long term by investment in battery vehicles. Reasons for siting such a system near to a public transport system and the initial consideration of other strategic issues have been given in chapter 9. The proposal to combine fuel cell powered electric rail systems carrying battery driven commercial delivery vehicles during their recharging phase appears to be advantageous, particularly in reducing pollution and congestion of heavy vehicles in the UK, especially those on long journeys from the European mainland.

Finally, a summary of the main conclusions. Fuel cells can yield significant environmental improvements, but selection of the cell type and fuel system and infrastructure is important. There could be an intermediate stage of introducing fuel cells in which they are used in a complementary role with battery vehicles and with existing transport fuels, which would need to be part of a long term strategy for improving emissions from the transport sector.

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TABLE A.1 FUEL CONSUMPTION FOR FUEL CELLS AND INTERNAL COMBUSTION ENGINES

EFFICIENCY	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
Fuel Cells:													
kgH2/kWh	.1501	.1201	.1001	.0858	.0750	.0667	.0600	.0546	.0500	.0462	.0429	.0400	.0375
kgCH4/kWh (Int. Reformed)	.2986	.2389	.1990	.1706	.1493	.1327	.1194	.1086	.0995	.0919	.0853	.0796	.0746
kgC3H8/kWh (Int. Reformed)	.3283	.2626	.2188	.1876	.1641	.1459	.1313	.1194	.1094	.1010	.0938	.0875	.0821
kgCH4/kWh (Reformed)	.3284	.2627	.2190	.1877	.1642	.1460	.1314	.1194	.1095	.1011	.0938	.0876	.0821
kgPetrol/kWh (Int. Reformed)	.3391	.2713	.2260	.1938	.1695	.1507	.1356	.1233	.1130	.1043	.0969	.0904	.0848
kgDiesel/kWh (Int. Reformed)	.3440	.2752	.2294	.1966	.1720	.1529	.1376	.1251	.1147	.1059	.0983	.0917	.0860
kgC3H8/kWh (Reformed)	.3611	.2889	.2407	.2063	.1805	.1605	.1444	.1313	.1204	.1111	.1032	.0963	.0903
kgPetrol/kWh (Reformed)	.3730	.2984	.2487	.2131	.1865	.1658	.1492	.1356	.1243	.1148	.1066	.0995	.0932
kgDiesel/kWh (Reformed)	.3784	.3027	.2523	.2162	.1892	.1682	.1514	.1376	.1261	.1164	.1081	.1009	.0946
kgCH4/kWh (Partial Oxidation)	.3981	.3185	.2654	.2275	.1990	.1769	.1592	.1448	.1327	.1225	.1137	.1062	.0995
kgRME/kWh (Int. Reformed)	.4040	.3232	.2694	.2309	.2020	.1796	.1616	.1469	.1347	.1243	.1154	.1077	.1010
kgRME/kWh (Reformed)	.4444	.3556	.2963	.2540	.2222	.1975	.1778	.1616	.1481	.1368	.1270	.1185	.1111
kgC3H8/kWh (Partial Oxidation)	.4690	.3752	.3126	.2680	.2345	.2084	.1876	.1705	.1563	.1443	.1340	.1251	.1172
kgPetrol/kWh (Partial Oxidation)	.4973	.3978	.3315	.2842	.2487	.2210	.1989	.1808	.1658	.1530	.1421	.1326	.1243
kgDiesel/kWh (Partial Oxidation)	.5108	.4087	.3406	.2919	.2554	.2270	.2043	.1858	.1703	.1572	.1460	.1362	.1277
kgRME/kWh (Partial Oxidation)	.5848	.4678	.3899	.3342	.2924	.2599	.2339	.2127	.1949	.1799	.1671	.1559	.1462
kgC2H5OH/kWh (Int. Reformed)	.5716	.4573	.3811	.3266	.2858	.2541	.2286	.2079	.1905	.1759	.1633	.1524	.1429
kgC2H5OH/kWh (Reformed)	.6288	.5030	.4192	.3593	.3144	.2795	.2515	.2286	.2096	.1935	.1796	.1677	.1572
kgCH3OH/kWh (Int. Reformed)	.7952	.6361	.5301	.4544	.3976	.3534	.3181	.2891	.2651	.2447	.2272	.2120	.1988
kgCH3OH/kWh (Reformed)	.8747	.6997	.5831	.4998	.4373	.3887	.3499	.3181	.2916	.2691	.2499	.2332	.2187
Internal Combustion Engines:													
kgH2/kWh	.1501	.1201	.1001	.0858	.0750	.0667							
kgCH4/kWh	.3599	.2879	.2399	.2056	.1799	.1599							
kgC3H8/kWh	.3967	.3174	.2645	.2267	.1984	.1763							
kgPetrol/kWh	.4111	.3289	.2741	.2349	.2056	.1827							
kgDiesel/kWh	.4460	.3568	.2973	.2548	.2230	.1982							
kgRME/kWh	.6065	.4852	.4043	.3466	.3032	.2695							
kgC2H5OH/kWh	.6739	.5391	.4493	.3851	.3370	.2995							
kgCH3OH/kWh	.9032	.7225	.6021	.5161	.4516	.4014							

TABLE A.2 ENERGY CONSUMPTION FOR FUEL CELLS AND INTERNAL COMBUSTION ENGINES

FUEL CELLS:													
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
kgH2/kWh	.1501	.1201	.1001	.0858	.0750	.0667	.0600	.0546	.0500	.0462	.0429	.0400	.0375
MJ/kWh (Use)	21.29	17.03	14.19	12.17	10.65	9.463	8.517	7.742	7.097	6.551	6.083	5.678	5.323
MJ/kWh (Electrolysis)	1.439	1.151	.9596	.8225	.7197	.6397	.5757	.5234	.4798	.4429	.4112	.3838	.3598
Total MJ/kWh (Hydrogen)	22.73	18.18	15.15	12.99	11.37	10.10	9.092	8.266	7.577	6.994	6.495	6.062	5.683
kg Petrol/kWh (Int. Reforming)	.3391	.2713	.2260	.1938	.1695	.1507	.1356	.1233	.1130	.1043	.0969	.0904	.0848
MJ/kWh (Use)	15.62	12.50	10.42	8.928	7.812	6.944	6.250	5.682	5.208	4.808	4.464	4.167	3.906
MJ/kWh (Manufacture)	2.637	2.110	1.758	1.507	1.319	1.172	1.055	.9591	.8791	.8115	.7535	.7033	.6593
Total MJ/kWh (Int. Ref. Petrol)	18.26	14.61	12.17	10.44	9.131	8.116	7.305	6.641	6.087	5.619	5.218	4.870	4.565
kgPetrol/kWh (Reformed)	.3730	.2984	.2487	.2131	.1865	.1658	.1492	.1356	.1243	.1148	.1066	.0995	.0932
MJ/kWh (Use)	17.19	13.75	11.46	9.821	8.593	7.639	6.875	6.250	5.729	5.288	4.911	4.583	4.297
MJ/kWh (Manufacture)	2.901	2.321	1.934	1.658	1.451	1.289	1.160	1.055	.9670	.8927	.8289	.7736	.7253
Total MJ/kWh (Ref. Petrol)	20.09	16.07	13.39	11.48	10.04	8.928	8.035	7.305	6.696	6.181	5.739	5.357	5.022
kgPetrol/kWh (Partial Oxidation)	.4973	.3978	.3315	.2842	.2487	.2210	.1989	.1808	.1658	.1530	.1421	.1326	.1243
MJ/kWh (Use)	22.92	18.33	15.28	13.09	11.46	10.18	9.166	8.333	7.639	7.051	6.547	6.111	5.729
MJ/kWh (Manufacture)	3.868	3.095	2.579	2.210	1.934	1.719	1.547	1.407	1.289	1.190	1.105	1.032	.9670
Total MJ/kWh (POx Petrol)	26.78	21.43	17.86	15.31	13.39	11.90	10.71	9.740	8.928	8.241	7.653	7.142	6.696
kgCH4/kWh (Int. Reforming)	.2986	.2389	.1990	.1706	.1493	.1327	.1194	.1086	.0995	.0919	.0853	.0796	.0746
MJ/kWh (Use)	16.59	13.27	11.06	9.478	8.293	7.371	6.634	6.031	5.529	5.103	4.739	4.423	4.146
MJ/kWh (Manufacture)	1.010	.8081	.6734	.5772	.5050	.4489	.4040	.3673	.3367	.3108	.2886	.2694	.2525
Total MJ/kWh (Int. Ref. CH4)	17.60	14.08	11.73	10.05	8.798	7.820	7.038	6.399	5.865	5.414	5.027	4.692	4.399
kgCH4/kWh (Reformed)	.3284	.2627	.2190	.1877	.1642	.1460	.1314	.1194	.1095	.1011	.0938	.0876	.0821
MJ/kWh (Use)	18.24	14.60	12.16	10.43	9.122	8.109	7.298	6.634	6.081	5.614	5.213	4.865	4.561
MJ/kWh (Manufacture)	1.111	.8889	.7407	.6349	.5555	.4938	.4444	.4040	.3704	.3419	.3175	.2963	.2778
Total MJ/kWh (Ref. CH4)	19.36	15.48	12.90	11.06	9.678	8.602	7.742	7.038	6.452	5.956	5.530	5.161	4.839

TABLE A.2 ENERGY CONSUMPTION FOR FUEL CELLS AND INTERNAL COMBUSTION ENGINES (Continued)

FUEL CELLS:													
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
kgCH4/kWh (Partial Oxidation)	.3981	.3185	.2654	.2275	.1990	.1769	.1592	.1448	.1327	.1225	.1137	.1062	.0995
MJ/kWh (Use)	22.11	17.69	14.74	12.64	11.06	9.829	8.846	8.042	7.371	6.804	6.318	5.897	5.529
MJ/kWh (Manufacture)	1.347	1.077	.8978	.7696	.6734	.5986	.5387	.4897	.4489	.4144	.3848	.3591	.3367
Total MJ/kWh (POx CH4)	23.46	18.77	15.64	13.41	11.73	10.43	9.384	8.531	7.820	7.219	6.703	6.256	5.865
kgC3H8/kWh (Int. Reforming)	.3280	.2624	.2187	.1874	.1640	.1458	.1312	.1193	.1093	.1009	.0937	.0875	.0820
MJ/kWh (Use)	16.54	13.23	11.02	9.449	8.268	7.349	6.614	6.013	5.512	5.088	4.725	4.410	4.134
MJ/kWh (Manufacture)	2.021	1.617	1.347	1.155	1.010	.8981	.8083	.7348	.6736	.6218	.5773	.5389	.5052
Total MJ/kWh (Int. Ref. C8H8)	18.56	14.85	12.37	10.60	9.278	8.248	7.423	6.748	6.186	5.710	5.302	4.949	4.639
kgC8H8/kWh (Reformed)	.3608	.2887	.2406	.2062	.1804	.1604	.1443	.1312	.1203	.1110	.1031	.0962	.0902
MJ/kWh (Use)	18.19	14.55	12.13	10.39	9.095	8.084	7.276	6.614	6.063	5.597	5.197	4.851	4.547
MJ/kWh (Manufacture)	2.223	1.778	1.482	1.270	1.111	.9879	.8891	.8083	.7409	.6839	.6351	.5927	.5557
Total MJ/kWh (Ref. C8H8)	20.41	16.33	13.61	11.66	10.21	9.072	8.165	7.423	6.804	6.281	5.832	5.443	5.103
kgC8H8/kWh (Partial Oxidation)	.4690	.3752	.3126	.2680	.2345	.2084	.1876	.1705	.1563	.1443	.1340	.1251	.1172
MJ/kWh (Use)	23.64	18.91	15.76	13.51	11.82	10.51	9.456	8.596	7.880	7.274	6.754	6.304	5.910
MJ/kWh (Manufacture)	2.889	2.311	1.926	1.651	1.444	1.284	1.156	1.050	.9629	.8889	.8254	.7704	.7222
Total MJ/kWh (Partial Oxidation)	26.53	21.22	17.69	15.16	13.26	11.79	10.61	9.647	8.843	8.163	7.580	7.074	6.632
kgDiesel/kWh (Int. Reforming)	.3440	.2752	.2294	.1966	.1720	.1529	.1376	.1251	.1147	.1059	.0983	.0917	.0860
MJ/kWh (Use)	15.27	12.22	10.18	8.729	7.637	6.789	6.110	5.555	5.092	4.700	4.364	4.073	3.819
MJ/kWh (Manufacture)	1.859	1.487	1.239	1.062	.9295	.8262	.7436	.6760	.6197	.5720	.5311	.4957	.4647
Total MJ/kWh (Int. Ref. Diesel)	17.13	13.71	11.42	9.791	8.567	7.615	6.854	6.230	5.711	5.272	4.895	4.569	4.283
kgDiesel/kWh (Reformed)	.3784	.3027	.2523	.2162	.1892	.1682	.1514	.1376	.1261	.1164	.1081	.1009	.0946
MJ/kWh (Use)	16.80	13.44	11.20	9.601	8.401	7.468	6.721	6.110	5.601	5.170	4.801	4.481	4.201
MJ/kWh (Manufacture)	2.045	1.636	1.363	1.168	1.022	.9088	.8179	.7436	.6816	.6292	.5842	.5453	.5112
Total MJ/kWh (Ref. Diesel)	18.85	15.08	12.56	10.77	9.424	8.377	7.539	6.854	6.282	5.799	5.385	5.026	4.712

TABLE A.2 ENERGY CONSUMPTION FOR FUEL CELLS AND INTERNAL COMBUSTION ENGINES (Continued)

FUEL CELLS:													
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
kgDiesel/kWh (Partial Oxidation)	.5108	.4087	.3406	.2919	.2554	.2270	.2043	.1858	.1703	.1572	.1460	.1362	.1277
MJ/kWh (Use)	22.68	18.14	15.12	12.96	11.34	10.08	9.072	8.248	7.560	6.979	6.480	6.048	5.670
MJ/kWh (Manufacture)	2.760	2.208	1.840	1.577	1.380	1.227	1.104	1.004	.9201	.8493	.7886	.7361	.6901
Total MJ/kWh (POx Diesel)	25.44	20.35	16.96	14.54	12.72	11.31	10.18	9.251	8.480	7.828	7.269	6.784	6.360
kgC2H5OH/kWh (Int. Reforming)	.5716	.4573	.3811	.3266	.2858	.2541	.2286	.2079	.1905	.1759	.1633	.1524	.1429
MJ/kWh (Use)	15.27	12.21	10.18	8.724	7.634	6.786	6.107	5.552	5.089	4.698	4.362	4.071	3.817
MJ/kWh (Ethanol from oil)	35.20	28.16	23.47	20.11	17.60	15.64	14.08	12.80	11.73	10.83	10.06	9.387	8.800
MJ/kWh (Bioethanol Man.)	9.883	7.906	6.588	5.647	4.941	4.392	3.953	3.594	3.294	3.041	2.824	2.635	2.471
Total MJ/kWh (Int. Ref. Ethanol)	50.47	40.37	33.65	28.84	25.23	22.43	20.19	18.35	16.82	15.53	14.42	13.46	12.62
Total MJ/kWh (Int. Ref. Bioeth.)	25.15	20.12	16.77	14.37	12.58	11.18	10.06	9.146	8.383	7.739	7.186	6.707	6.288
kgC2H5OH/kWh (Reformed)	.6288	.5030	.4192	.3593	.3144	.2795	.2515	.2286	.2096	.1935	.1796	.1677	.1572
MJ/kWh (Use)	21.32	17.05	14.21	12.18	10.66	9.474	8.526	7.751	7.105	6.559	6.090	5.684	5.329
MJ/kWh (Ethanol from oil)	38.72	30.98	25.81	22.13	19.36	17.21	15.49	14.08	12.91	11.91	11.06	10.33	9.680
MJ/kWh (Bioethanol Man.)	10.87	8.697	7.247	6.212	5.435	4.832	4.348	3.953	3.624	3.345	3.106	2.899	2.718
Total MJ/kWh (Ref. Ethanol)	60.04	48.03	40.02	34.31	30.02	26.68	24.01	21.83	20.01	18.47	17.15	16.01	15.01
Total MJ/kWh (Ref. Bioeth.)	32.19	25.75	21.46	18.39	16.09	14.31	12.87	11.70	10.73	9.903	9.196	8.583	8.047
kgCH3OH/kWh (Int. Reformed)	.7952	.6361	.5301	.4544	.3976	.3534	.3181	.2891	.2651	.2447	.2272	.2120	.1988
MJ/kWh (Use)	18.04	14.43	12.03	10.31	9.021	8.019	7.217	6.561	6.014	5.551	5.155	4.811	4.511
MJ/kWh (Methanol from oil)	34.18	27.35	22.79	19.53	17.09	15.19	13.67	12.43	11.39	10.52	9.767	9.116	8.546
MJ/kWh (Biomethanol Man.)	9.274	7.419	6.182	5.299	4.637	4.122	3.709	3.372	3.091	2.853	2.650	2.473	2.318
Total MJ/kWh (Int. Ref. Meth.)	52.23	41.78	34.82	29.84	26.11	23.21	20.89	18.99	17.41	16.07	14.92	13.93	13.06
Total MJ/kWh (Int. Ref. Biometh.)	27.32	21.85	18.21	15.61	13.66	12.14	10.93	9.933	9.105	8.405	7.804	7.284	6.829

TABLE A.2 ENERGY CONSUMPTION FOR FUEL CELLS AND INTERNAL COMBUSTION ENGINES (Continued)

FUEL CELLS:													
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
kgCH3OH/kWh (Reformed)	.8747	.6997	.5831	.4998	.4373	.3887	.3499	.3181	.2916	.2691	.2499	.2332	.2187
MJ/kWh (Use)	19.85	15.88	13.23	11.34	9.923	8.821	7.939	7.217	6.615	6.107	5.670	5.292	4.962
MJ/kWh (Methanol from oil)	37.60	30.08	25.07	21.49	18.80	16.71	15.04	13.67	12.53	11.57	10.74	10.03	9.401
MJ/kWh (Biomethanol Man.)	10.20	8.161	6.801	5.829	5.101	4.534	4.080	3.709	3.400	3.139	2.915	2.720	2.550
Total MJ/kWh (Ref. Methanol)	57.45	45.96	38.30	32.83	28.72	25.53	22.98	20.89	19.15	17.68	16.41	15.32	14.36
Total MJ/kWh (Ref. Biometh.)	30.05	24.04	20.03	17.17	15.02	13.35	12.02	10.93	10.02	9.245	8.585	8.013	7.512
kgRME/kWh (Internal Reforming)	.4040	.3232	.2694	.2309	.2020	.1796	.1616	.1469	.1347	.1243	.1154	.1077	.1010
MJ/kWh (Use)	14.99	11.99	9.993	8.566	7.495	6.662	5.996	5.451	4.997	4.612	4.283	3.997	3.747
MJ/kWh (Manufacture)	9.893	7.915	6.595	5.653	4.947	4.397	3.957	3.598	3.298	3.044	2.827	2.638	2.473
Total MJ/kWh (Int. Ref. RME)	24.88	19.91	16.59	14.22	12.44	11.06	9.953	9.048	8.294	7.656	7.109	6.635	6.221
kgRME/kWh (Reformed)	.4444	.3556	.2963	.2540	.2222	.1975	.1778	.1616	.1481	.1368	.1270	.1185	.1111
MJ/kWh (Use)	16.49	13.19	10.99	9.422	8.244	7.328	6.595	5.996	5.496	5.073	4.711	4.397	4.122
MJ/kWh (Manufacture)	10.88	8.706	7.255	6.219	5.441	4.837	4.353	3.957	3.628	3.348	3.109	2.902	2.721
Total MJ/kWh (Ref. RME)	27.37	21.90	18.25	15.64	13.69	12.16	10.95	9.953	9.124	8.422	7.820	7.299	6.843
kgRME/kWh (Partial Oxidation)	.5848	.4678	.3899	.3342	.2924	.2599	.2339	.2127	.1949	.1799	.1671	.1559	.1462
MJ/kWh (Use)	21.70	17.36	14.46	12.40	10.85	9.643	8.678	7.889	7.232	6.676	6.199	5.786	5.424
MJ/kWh (Manufacture)	14.32	11.46	9.546	8.183	7.160	6.364	5.728	5.207	4.773	4.406	4.091	3.819	3.580
Total MJ/kWh (POx RME)	36.02	28.81	24.01	20.58	18.01	16.01	14.41	13.10	12.01	11.08	10.29	9.604	9.004
INTERNAL COMBUSTION ENGINES:													
kgPetrol/kWh	.4111	.3289	.2741	.2349	.2056	.1827							
MJ/kWh (Use)	18.95	15.16	12.63	10.83	9.473	8.420							
MJ/kWh (Manufacture)	3.198	2.558	2.132	1.827	1.599	1.421							
Total MJ/kWh (Petrol)	22.14	17.71	14.76	12.65	11.07	9.842							
kgCH4/kWh	.3599	.2879	.2399	.2056	.1799	.1599							
MJ/kWh (Use)	19.99	15.99	13.33	11.42	9.995	8.884							
MJ/kWh (Manufacture)	1.217	.9739	.8116	.6957	.6087	.5411							
Total MJ/kWh (CH4)	21.21	16.97	14.14	12.12	10.60	9.426							

TABLE A.2 ENERGY CONSUMPTION FOR FUEL CELLS AND INTERNAL COMBUSTION ENGINES (Continued)

Efficiency						
kgC8H8/kWh	.3967	.3174	.2645	.2267	.1984	.1763
MJ/kWh (Use)	20.00	16.00	13.33	11.43	10.00	8.889
MJ/kWh (Manufacture)	2.444	1.955	1.629	1.397	1.222	1.086
Total MJ/kWh (C8H8)	22.44	17.95	14.96	12.82	11.22	9.975
kgDiesel/kWh	.4460	.3568	.2973	.2548	.2230	.1982
MJ/kWh (Use)	19.80	15.84	13.20	11.32	9.901	8.801
Manufacture)	2.410	1.928	1.607	1.377	1.205	1.071
Total MJ/kWh (Diesel)	22.21	17.77	14.81	12.69	11.11	9.872
kgC2H5OH/kWh	.6739	.5391	.4493	.3851	.3370	.2995
MJ/kWh (Use)	22.85	18.28	15.23	13.05	11.42	10.15
MJ/kWh Ethanol from Oil)	41.50	33.20	27.67	23.71	20.75	18.44
MJ/kWh (Bioethanol Man.)	11.65	9.321	7.767	6.658	5.826	5.178
Total MJ/kWh (Ethanol)	64.34	51.48	42.90	36.77	32.17	28.60
Total MJ/kWh (Bioethanol)	34.50	27.60	23.00	19.71	17.25	15.33
kgCH3OH/kWh	.9032	.7225	.6021	.5161	.4516	.4014
MJ/kWh (Use)	20.49	16.39	13.66	11.71	10.25	9.108
MJ/kWh (Methanol from Oil)	38.83	31.06	25.88	22.19	19.41	17.26
MJ/kWh (Biomethanol Man.)	10.53	8.427	7.022	6.019	5.267	4.681
Total MJ/kWh (Methanol)	59.32	47.46	39.55	33.90	29.66	26.36
Total MJ/kWh (Biomethanol)	31.03	24.82	20.68	17.73	15.51	13.79
kgRME/kWh	.6065	.4852	.4043	.3466	.3032	.2695
MJ/kWh (Use)	22.5	18	15	12.86	11.25	10
MJ/kWh (Manufacture)	14.85	11.88	9.9	8.486	7.425	6.6
Total MJ/kWh (RME)	37.35	29.88	24.9	21.34	18.68	16.6
kgH2/kWh	.1501	.1201	.1001	.0858	.0750	.0667
MJ/kWh (Use)	21.29	17.03	14.19	12.17	10.65	9.463
MJ/kWh (Electrolysis)	1.439	1.151	.9596	.8225	.7197	.6397
Total MJ/kWh (H2)	22.73	18.18	15.15	12.99	11.37	10.10

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TABLE A.3 CARBON DIOXIDE EMISSIONS FOR DIFFERENT FUELS

kg CO2/kWh (Use):													
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC RME (Partial Oxidation)	1.638	1.311	1.092	.9361	.8191	.7281	.6553	.5957	.5461	.5041	.4681	.4369	.4095
FC Diesel (Partial Oxidation)	1.589	1.271	1.059	.9078	.7943	.7060	.6354	.5777	.5295	.4888	.4539	.4236	.3971
FC Petrol (Partial Oxidation)	1.529	1.223	1.019	.8737	.7645	.6796	.6116	.5560	.5097	.4705	.4369	.4077	.3823
FC Propane (Partial Oxidation)	1.404	1.123	.9361	.8024	.7021	.6241	.5617	.5106	.4681	.4321	.4012	.3745	.3510
FC RME (Steamed Reformed)	1.246	.9965	.8304	.7118	.6228	.5536	.4982	.4529	.4152	.3833	.3559	.3322	.3114
FC Methanol (Steam Reformed)	1.200	.9600	.8000	.6857	.6000	.5334	.4800	.4364	.4000	.3692	.3429	.3200	.3000
FC Ethanol (Steam Reformed)	1.202	.9617	.8014	.6870	.6011	.5343	.4809	.4372	.4007	.3699	.3435	.3206	.3005
FC Diesel (Steam Reformed)	1.180	.9436	.7864	.6740	.5898	.5242	.4718	.4289	.3932	.3629	.3370	.3145	.2949
FC Petrol (Steam Reformed)	1.145	.9158	.7631	.6541	.5724	.5088	.4579	.4163	.3816	.3522	.3271	.3053	.2862
FC RME (Internally Reformed)	1.132	.9055	.7546	.6468	.5659	.5031	.4527	.4116	.3773	.3483	.3234	.3018	.2830
FC Diesel (Internally Reformed)	1.070	.8559	.7132	.6114	.5349	.4755	.4279	.3890	.3566	.3292	.3057	.2853	.2675
FC Methane (Partial Oxidation)	1.092	.8737	.7281	.6241	.5461	.4854	.4369	.3971	.3641	.3360	.3120	.2912	.2730
FC Ethanol (Internally Reformed)	1.093	.8741	.7284	.6243	.5463	.4856	.4370	.3973	.3642	.3362	.3122	.2914	.2731
FC Methanol (Internally Reformed)	1.092	.8737	.7281	.6241	.5461	.4854	.4369	.3971	.3641	.3360	.3120	.2912	.2730
FC Petrol (Internally Reformed)	1.043	.8340	.6950	.5957	.5213	.4633	.4170	.3791	.3475	.3208	.2979	.2780	.2606
FC Propane (Steam Reformed)	1.085	.8681	.7235	.6201	.5426	.4823	.4341	.3946	.3617	.3339	.3101	.2894	.2713
FC Propane (Internally Reformed)	.9867	.7894	.6578	.5638	.4933	.4385	.3947	.3588	.3289	.3036	.2819	.2631	.2467
FC Methane (Internally Reformed)	.8191	.6553	.5461	.4681	.4096	.3641	.3276	.2979	.2730	.2520	.2340	.2184	.2048
FC Methane (Steam Reformed)	.9012	.7210	.6008	.5150	.4506	.4005	.3605	.3277	.3004	.2773	.2575	.2403	.2253
ICE Diesel	1.422	1.137	.9479	.8125	.7109	.6319							
ICE RME	1.707	1.366	1.138	.9755	.8536	.7588							
ICE Ethanol	1.289	1.031	.8595	.7367	.6446	.5730							
ICE Petrol	1.239	.9915	.8263	.7082	.6197	.5508							
ICE Methanol	1.242	.9935	.8279	.7096	.6209	.5519							
ICE Propane	1.190	.9522	.7935	.6801	.5951	.5290							
ICE Methane	.9896	.7917	.6597	.5655	.4948	.4398							

TABLE A.3 CARBON DIOXIDE EMISSIONS FOR DIFFERENT FUELS (Continued)

kgCO2/kWh (Total):														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
Batt. CHarge (24hrs)									1.079	.9957	.9246	.8630	.8090	.7614
Batt. Charge (Night)									.9446	.8720	.8097	.7557	.7085	.6668
FC RME (Partial Oxidation)	2.079	1.663	1.386	1.188	1.040	.9241	.8317	.7561	.6931	.6398	.5941	.5545	.5198	
FC Petrol (Partial Oxidation)	1.765	1.412	1.177	1.009	.8825	.7845	.7060	.6418	.5883	.5431	.5043	.4707	.4413	
FC Diesel (Partial Oxidation)	1.745	1.396	1.163	.9970	.8724	.7755	.6979	.6345	.5816	.5369	.4985	.4653	.4362	
FC Biomethanol (Steam Reformed)	2.002	1.602	1.335	1.144	1.001	.8899	.8009	.7281	.6674	.6161	.5721	.5339	.5006	
FC RME (Steam Reformed)	1.581	1.265	1.054	.9033	.7904	.7026	.6323	.5748	.5269	.4864	.4517	.4215	.3952	
FC Bioethanol (Steam Reformed)	1.641	1.313	1.094	.9376	.8204	.7293	.6563	.5967	.5469	.5049	.4688	.4376	.4102	
FC Propane (Partial Oxidation)	1.584	1.267	1.056	.9051	.7919	.7039	.6335	.5760	.5280	.4873	.4525	.4224	.3960	
FC Biomethanol (Internally Reformed)	1.580	1.264	1.054	.9030	.7901	.7023	.6321	.5746	.5268	.4862	.4515	.4214	.3951	
FC RME (Internally Reformed)	1.437	1.149	.9578	.8209	.7183	.6385	.5747	.5224	.4789	.4420	.4105	.3831	.3592	
FC Bioethanol (Internally Reformed)	1.491	1.193	.9943	.8522	.7457	.6628	.5966	.5423	.4971	.4589	.4261	.3977	.3728	
FC Methanol (Steam Reformed)	1.339	1.071	.8927	.7651	.6695	.5951	.5356	.4869	.4463	.4120	.3826	.3571	.3347	
FC Petrol (Steam Reformed)	1.322	1.057	.8812	.7553	.6609	.5874	.5287	.4806	.4406	.4067	.3776	.3525	.3304	
FC Diesel (Steam Reformed)	1.295	1.036	.8637	.7403	.6477	.5758	.5182	.4711	.4318	.3986	.3701	.3455	.3239	
FC Petrol (Internally Reformed)	1.279	1.023	.8524	.7306	.6393	.5682	.5114	.4649	.4262	.3934	.3653	.3409	.3196	
FC Diesel (Internally Reformed)	1.226	.9809	.8174	.7006	.6130	.5449	.4904	.4458	.4087	.3773	.3503	.3270	.3065	
FC Propane (Steam Reformed)	1.224	.9788	.8157	.6992	.6118	.5438	.4894	.4449	.4078	.3765	.3496	.3263	.3059	
FC Methanol (Internally Reformed)	1.218	.9748	.8123	.6963	.6092	.5415	.4874	.4431	.4061	.3749	.3481	.3249	.3046	
FC Methane (Partial Oxidation)	1.198	.9586	.7989	.6847	.5992	.5326	.4793	.4357	.3994	.3687	.3424	.3195	.2996	
FC Propane (Internally Reformed)	1.112	.8900	.7416	.6357	.5562	.4944	.4450	.4045	.3708	.3423	.3178	.2967	.2781	
FC Methane (Steam Reformed)	.9888	.7910	.6592	.5650	.4944	.4395	.3955	.3596	.3296	.3042	.2825	.2637	.2472	
FC Methane (Internally Reformed)	.9253	.7402	.6168	.5287	.4626	.4112	.3701	.3365	.3084	.2847	.2644	.2467	.2313	
Hydrogen (Electrolysis)	.2911	.2329	.1940	.1663	.1455	.1294	.1164	.1058	.0970	.0896	.0832	.0776	.0728	
ICE Biomethanol	1.796	1.437	1.198	1.026	.8981	.7983								
ICE RME	2.165	1.732	1.443	1.237	1.082	.9621								
ICE Bioethanol	1.759	1.407	1.173	1.005	.8796	.7818								
ICE Diesel	1.558	1.247	1.039	.8905	.7792	.6926								
ICE Petrol	1.435	1.148	.9564	.8197	.7173	.6376								
ICE Methanol	1.385	1.108	.9235	.7916	.6926	.6157								
ICE Propane	1.342	1.074	.8948	.7670	.6711	.5965								
ICE Methane	1.086	.8684	.7237	.6203	.5428	.4825								

TABLE A.4 CARBON MONOXIDE EMISSIONS FOR DIFFERENT FUELS

g CO/kWh (Use):

Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC Petrol (Reformed)	1.512	1.210	1.008	.8640	.7560	.6720	.6048	.5498	.5040	.4652	.4320	.4032	.3780
FC Ethanol (Reformed)	1.355	1.084	.9032	.7742	.6774	.6021	.5419	.4927	.4516	.4169	.3871	.3613	.3387
FC RME (Reformed)	.9552	.7641	.6368	.5458	.4776	.4245	.3821	.3473	.3184	.2939	.2729	.2547	.2388
FC Diesel (Reformed)	.7569	.6055	.5046	.4325	.3784	.3364	.3027	.2752	.2523	.2329	.2162	.2018	.1892
FC Biomethanol (Reformed)	.4850	.3880	.3234	.2772	.2425	.2156	.1940	.1764	.1617	.1492	.1386	.1293	.1213
FC Methane (Reformed)	.1493	.1194	.0995	.0853	.0746	.0663	.0597	.0543	.0498	.0459	.0427	.0398	.0373
FC Propane (Reformed)	.1418	.1134	.0945	.0810	.0709	.0630	.0567	.0515	.0473	.0436	.0405	.0378	.0354
Hydrogen (Electrolysis)	.0815	.0652	.0543	.0466	.0407	.0362	.0326	.0296	.0272	.0251	.0233	.0217	.0204
ICE Petrol	18.33	14.67	12.22	10.48	9.167	8.148							
ICE Ethanol	15.93	12.74	10.62	9.103	7.966	7.080							
ICE Diesel	9.812	7.849	6.541	5.607	4.906	4.361							
ICE RME	8.812	7.050	5.875	5.035	4.406	3.916							
ICE Methanol	5.509	4.407	3.673	3.148	2.755	2.449							
ICE Methane	1.799	1.439	1.200	1.028	.8996	.7997							
ICE Propane	1.706	1.365	1.137	.9748	.8530	.7582							

TABLE A.4 CARBON MONOXIDE EMISSIONS (Continued)

g CO/kWh (Total):

Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Bioethanol (Reformed)	3.793	3.035	2.529	2.168	1.897	1.686	1.517	1.379	1.264	1.167	1.084	1.012	.9483	
FC RME (Reformed)	2.446	1.957	1.631	1.398	1.223	1.087	.9783	.8894	.8153	.7525	.6988	.6522	.6114	
FC RME (Partial Oxidation)	1.961	1.569	1.308	1.121	.9807	.8717	.7845	.7132	.6538	.6035	.5604	.5230	.4903	
FC Bioethanol (Int. Reformed)	2.211	1.769	1.474	1.263	1.105	.9827	.8844	.8040	.7370	.6803	.6317	.5896	.5527	
FC Petrol (Reformed)	1.598	1.278	1.065	.9131	.7989	.7102	.6391	.5810	.5326	.4916	.4565	.4261	.3995	
FC RME (Int. Reformed)	1.355	1.084	.9034	.7743	.6775	.6023	.5420	.4928	.4517	.4170	.3872	.3614	.3388	
FC Biomethanol (Reformed)	.9574	.7659	.6383	.5471	.4787	.4255	.3830	.3481	.3191	.2946	.2735	.2553	.2393	
FC Diesel (Reformed)	.8274	.6619	.5516	.4728	.4137	.3677	.3310	.3009	.2758	.2546	.2364	.2206	.2069	
FC Methanol (Reformed)	.5644	.4515	.3763	.3225	.2822	.2509	.2258	.2052	.1881	.1737	.1613	.1505	.1411	
FC Biomethanol (Int. Reformed)	.4723	.3779	.3149	.2699	.2362	.2099	.1889	.1718	.1574	.1453	.1350	.1260	.1181	
FC Propane (Reformed)	.2478	.1982	.1652	.1416	.1239	.1101	.0991	.0901	.0826	.0762	.0708	.0661	.0619	
FC Methane (Reformed)	.1840	.1472	.1226	.1051	.0920	.0818	.0736	.0669	.0613	.0566	.0526	.0491	.0460	
FC Propane (Partial Oxidation)	.1371	.1097	.0914	.0784	.0686	.0609	.0548	.0499	.0457	.0422	.0392	.0366	.0343	
FC Petrol (Partial Oxidation)	.1146	.0922	.0768	.0659	.0576	.0512	.0461	.0419	.0384	.0355	.0329	.0307	.0288	
FC Diesel (Partial Oxidation)	.0953	.0762	.0635	.0544	.0476	.0423	.0381	.0346	.0318	.0293	.0272	.0254	.0238	
FC Propane (Int. Reformed)	.0960	.0768	.0640	.0548	.0480	.0427	.0384	.0349	.0320	.0295	.0274	.0256	.0240	
Hydrogen (Electrolysis)	.0815	.0652	.0543	.0466	.0407	.0362	.0326	.0296	.0272	.0251	.0233	.0217	.0204	
FC Petrol (Int. Reformed)	.0781	.0625	.0521	.0446	.0391	.0347	.0312	.0284	.0260	.0240	.0223	.0208	.0195	
FC Methanol (Int. Reformed)	.0722	.0577	.0481	.0412	.0361	.0321	.0289	.0262	.0241	.0222	.0206	.0192	.0180	
FC Diesel (Int. Reformed)	.0642	.0513	.0428	.0367	.0321	.0285	.0257	.0233	.0214	.0197	.0183	.0171	.0160	
FC Methane (Partial Oxidation)	.0420	.0336	.0280	.0240	.0210	.0187	.0168	.0153	.0140	.0129	.0120	.0112	.0105	
FC Methane (Int. Reformed)	.0315	.0252	.0210	.0180	.0158	.0140	.0126	.0115	.0105	.0097	.0090	.0084	.0079	
Batt. Charge (24hrs)									.302	.2788	.2589	.2416	.2265	.2132
Batt. Charge (Night)									.3	.2769	.2571	.24	.225	.2118
Petrol ICE	18.43	14.74	12.29	10.53	9.214	8.190								
ICE Bioethanol	18.54	14.83	12.36	10.59	9.269	8.239								
ICE Diesel	9.895	7.916	6.597	5.654	4.947	4.398								
ICE RME	10.85	8.677	7.231	6.198	5.423	4.820								
ICE Biomethanol	5.997	4.798	3.998	3.427	2.999	2.665								
ICE Methanol	5.591	4.473	3.728	3.195	2.796	2.485								
ICE Methane	1.837	1.470	1.225	1.050	.9186	.8166								
ICE Propane	1.822	1.458	1.215	1.041	.9110	.8098								

TABLE A.5 METHANE EMISSIONS FOR DIFFERENT FUELS

g Methane/kWh (Use):

Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC Methane (Reformed)	.3971	.3177	.2647	.2269	.1986	.1765	.1588	.1444	.1324	.1222	.1135	.1059	.0993
FC Propane (Reformed)	.0198	.0158	.0132	.0113	.0099	.0088	.0079	.0072	.0066	.0061	.0057	.0053	.0049
FC Methanol (Reformed)	.0159	.0127	.0106	.0091	.0080	.0071	.0064	.0058	.0053	.0049	.0045	.0042	.0040
FC Ethanol (Reformed)	.0114	.0091	.0076	.0065	.0057	.0051	.0046	.0042	.0038	.0035	.0033	.0030	.0029
FC Petrol (Reformed)	.0106	.0085	.0071	.0060	.0053	.0047	.0042	.0038	.0035	.0033	.0030	.0028	.0026
FC Diesel (Reformed)	.0065	.0052	.0044	.0037	.0033	.0029	.0026	.0024	.0022	.0020	.0019	.0017	.0016
ICE Methane	5.398	4.318	3.599	3.084	2.699	2.399							
ICE Propane	.2380	.1904	.1587	.1360	.1190	.1058							
ICE Methanol	.1806	.1445	.1204	.1032	.0903	.0803							
ICE Ethanol	.1348	.1078	.0899	.0770	.0674	.0599							
ICE Petrol	.1283	.1026	.0855	.0733	.0641	.0570							
ICE Diesel	.0847	.0678	.0565	.0484	.0424	.0377							

TABLE A.5 METHANE EMISSIONS FOR DIFFERENT FUELS (Continued)

g Methane/kWh (Total):														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Methane (Partial Oxidation	4.847	3.877	3.231	2.770	2.423	2.154	1.939	1.762	1.616	1.491	1.385	1.292	1.212	
FC Methane (Reformed)	4.374	3.500	2.916	2.500	2.187	1.944	1.750	1.591	1.458	1.346	1.250	1.167	1.094	
FC Methane (Int. Ref.)	3.635	2.908	2.423	2.077	1.818	1.616	1.454	1.322	1.212	1.118	1.039	.9694	.9088	
Hydrogen (Electrolysis)	.8621	.6896	.5747	.4926	.4310	.3831	.3448	.3135	.2874	.2652	.2463	.2299	.2155	
FC Propane (Partial Oxidation)	.4042	.3234	.2695	.2310	.2021	.1797	.1617	.1470	.1347	.1244	.1155	.1078	.1011	
FC Petrol (Partial Oxidation)	.3596	.2877	.2398	.2055	.1798	.1598	.1439	.1308	.1199	.1107	.1028	.0959	.0899	
FC Diesel (Partial Oxidation)	.3332	.2665	.2221	.1904	.1666	.1481	.1333	.1211	.1111	.1025	.0952	.0888	.0833	
FC Propane (Reformed)	.3307	.2646	.2205	.1890	.1654	.1470	.1323	.1203	.1102	.1018	.0945	.0882	.0827	
FC Petrol (Reformed)	.2787	.2230	.1858	.1593	.1393	.1239	.1115	.1013	.0929	.0858	.0796	.0743	.0697	
FC Propane (Int. Ref.)	.2830	.2264	.1886	.1617	.1415	.1258	.1132	.1029	.0943	.0871	.0808	.0755	.0707	
FC Diesel (Reformed)	.2519	.2015	.1679	.1439	.1259	.1119	.1007	.0916	.0840	.0775	.0720	.0672	.0630	
FC Petrol (Int. Ref.)	.2165	.1732	.1443	.1237	.1082	.0962	.0866	.0787	.0722	.0666	.0618	.0577	.0541	
FC Diesel (Int. Ref.)	.2244	.1795	.1496	.1282	.1122	.0997	.0897	.0816	.0748	.0690	.0641	.0598	.0561	
FC Methanol (Reformed)	1.840	1.828	1.821	1.816	1.812	1.809	1.806	1.804	1.803	1.801	1.800	1.799	1.798	
FC Methanol (Int. Ref.)	1.674	1.663	1.656	1.652	1.648	1.645	1.643	1.641	1.639	1.638	1.637	1.636	1.635	
FC Biomethanol (Reformed)	.0159	.0127	.0106	.0091	.0080	.0071	.0064	.0058	.0053	.0049	.0045	.0042	.0040	
FC Bioethanol (Reformed)	.0114	.0091	.0076	.0065	.0057	.0051	.0046	.0042	.0038	.0035	.0033	.0030	.0029	
Batt. Charge (24hrs)									3.195	2.949	2.738	2.556	2.396	2.255
Batt. Charge (Night)									2.999	2.769	2.571	2.399	2.250	2.117
ICE Methane	9.756	7.805	6.504	5.575	4.878	4.336								
ICE Propane	.5780	.4624	.3854	.3303	.2890	.2569								
ICE Petrol	.3892	.3114	.2595	.2224	.1946	.1730								
ICE Diesel	.3738	.2991	.2492	.2136	.1869	.1662								
ICE Methanol	3.359	3.314	3.285	3.264	3.248	3.235								
ICE Biomethanol	.1806	.1445	.1204	.1032	.0903	.0803								
ICE Bioethanol	.1348	.1078	.0899	.0770	.0674	.0599								

TABLE A.6 NMVOC EMISSIONS FOR DIFFERENT FUELS

Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
g NMVOC/kWh (Use):													
FC Reformed Petrol	.2028	.1622	.1352	.1159	.1014	.0901	.0811	.0737	.0676	.0624	.0579	.0541	.0507
FC Methanol (Reformed)	.1829	.1463	.1219	.1045	.0914	.0813	.0732	.0665	.0610	.0563	.0523	.0488	.0457
FC Diesel (Reformed)	.1407	.1126	.0938	.0804	.0704	.0625	.0563	.0512	.0469	.0433	.0402	.0375	.0352
FC RME (Reformed)	.1374	.1099	.0916	.0785	.0687	.0611	.0549	.0500	.0458	.0423	.0392	.0366	.0343
FC Ethanol (Reformed)	.1315	.1052	.0876	.0751	.0657	.0584	.0526	.0478	.0438	.0405	.0376	.0351	.0329
FC Propane (Reformed)	.0985	.0788	.0657	.0563	.0492	.0438	.0394	.0358	.0328	.0303	.0281	.0263	.0246
FC Methane (Reformed)	.0388	.0311	.0259	.0222	.0194	.0173	.0155	.0141	.0129	.0119	.0111	.0104	.0097
ICE RME	3.778	3.023	2.519	2.159	1.889	1.679							
ICE Petrol	2.459	1.967	1.639	1.405	1.229	1.093							
ICE Ethanol	2.291	1.833	1.528	1.309	1.146	1.018							
ICE Methanol	2.077	1.662	1.385	1.187	1.039	.9232							
ICE Diesel	1.824	1.459	1.216	1.042	.9120	.8107							
ICE Propane	1.190	.9522	.7935	.6801	.5951	.5290							
ICE Methane	.4678	.3743	.3119	.2673	.2339	.2079							

TABLE A.6 NMVOC EMISSIONS FOR DIFFERENT FUELS (Continued)

g NMVOC/kWh (Total):														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Biomethanol (Reformed)	4.178	3.342	2.785	2.387	2.089	1.857	1.671	1.519	1.393	1.286	1.194	1.114	1.044	
FC Biomethanol (Int. Reformed)	3.632	2.905	2.421	2.075	1.816	1.614	1.453	1.321	1.211	1.117	1.038	.9685	.9080	
FC Petrol (Partial Oxidation)	4.854	3.883	3.236	2.773	2.427	2.157	1.941	1.765	1.618	1.493	1.387	1.294	1.213	
FC Petrol (Reformed)	3.843	3.074	2.562	2.196	1.921	1.708	1.537	1.397	1.281	1.182	1.098	1.025	.9607	
FC Petrol (Int. Reformed)	3.309	2.647	2.206	1.891	1.655	1.471	1.324	1.203	1.103	1.018	.9455	.8825	.8273	
FC Bioethanol (Reformed)	2.472	1.978	1.648	1.413	1.236	1.099	.9888	.8989	.8240	.7606	.7063	.6592	.6180	
FC Diesel (Partial Oxidation)	2.078	1.662	1.385	1.187	1.039	.9234	.8310	.7555	.6925	.6393	.5936	.5540	.5194	
FC Bioethanol (Int. Reformed)	2.128	1.702	1.418	1.216	1.064	.9456	.8511	.7737	.7092	.6547	.6079	.5674	.5319	
FC RME (Partial Oxidation)	1.679	1.343	1.120	.9596	.8397	.7464	.6717	.6107	.5598	.5167	.4798	.4478	.4198	
FC Diesel (Reformed)	1.680	1.344	1.120	.9599	.8399	.7466	.6719	.6108	.5599	.5169	.4799	.4479	.4200	
FC Propane (Partial Oxidation)	1.518	1.214	1.012	.8673	.7589	.6745	.6071	.5519	.5059	.4670	.4336	.4047	.3794	
FC Diesel (Int. Reformed)	1.399	1.119	.9328	.7995	.6996	.6219	.5597	.5088	.4664	.4305	.3998	.3731	.3498	
FC RME (Reformed)	1.276	1.021	.8508	.7293	.6381	.5672	.5105	.4641	.4254	.3927	.3646	.3403	.3191	
FC Propane (Reformed)	1.267	1.014	.8447	.7241	.6336	.5632	.5068	.4608	.4224	.3899	.3620	.3379	.3168	
FC RME (Int. Reformed)	1.160	.9282	.7735	.6630	.5801	.5156	.4641	.4219	.3867	.3570	.3315	.3094	.2901	
FC Propane (Int. Reformed)	1.062	.8499	.7083	.6071	.5312	.4722	.4250	.3863	.3541	.3269	.3035	.2833	.2656	
FC Methane (Partial Oxidation)	.8116	.6493	.5411	.4638	.4058	.3607	.3246	.2951	.2705	.2497	.2319	.2164	.2029	
FC Methane (Reformed)	.7084	.5667	.4723	.4048	.3542	.3148	.2834	.2576	.2361	.2180	.2024	.1889	.1771	
FC Methane (Int. Reformed)	.6087	.4870	.4058	.3478	.3043	.2705	.2435	.2213	.2029	.1873	.1739	.1623	.1522	
H2 (Electrolysis)	.0148	.0118	.0098	.0084	.0074	.0066	.0059	.0054	.0049	.0045	.0042	.0039	.0037	
Batt. Charge (24hrs)									.0547	.0505	.0469	.0437	.041	.0386
Batt. Charge (Night)									.0373	.0345	.032	.0299	.028	.0264
ICE Biomethanol	3.954	3.164	2.636	2.260	1.977	1.758								
ICE Petrol	6.001	4.801	4.001	3.429	3.001	2.667								
ICE Bioethanol	4.800	3.840	3.200	2.743	2.400	2.133								
ICE Diesel	3.638	2.910	2.425	2.079	1.819	1.617								
ICE RME	3.863	3.077	2.557	2.187	1.910	1.696								
ICE Propane	2.474	1.979	1.649	1.414	1.237	1.100								
ICE Ethanol	2.344	1.867	1.551	1.326	1.159	1.029								
ICE Methane	2.309	1.847	1.539	1.319	1.155	1.026								

TABLE A.7 NOx EMISSIONS FOR DIFFERENT FUELS

g NOx/KWh (Use):													
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC RME (Reformed)	.7564	.6051	.5042	.4322	.3782	.3362	.3025	.2750	.2521	.2327	.2161	.2017	.1891
FC Bioethanol (Reformed)	.8368	.6695	.5579	.4782	.4184	.3719	.3347	.3043	.2789	.2575	.2391	.2232	.2092
FC Diesel (Reformed)	.5597	.4478	.3732	.3198	.2799	.2488	.2239	.2035	.1866	.1722	.1599	.1493	.1399
FC Methanol (Reformed)	.4850	.3880	.3234	.2772	.2425	.2156	.1940	.1764	.1617	.1492	.1386	.1293	.1213
FC Methane (Reformed)	.3971	.3177	.2647	.2269	.1986	.1765	.1588	.1444	.1324	.1222	.1135	.1059	.0993
FC Propane (Reformed)	.3703	.2962	.2469	.2116	.1852	.1646	.1481	.1347	.1234	.1139	.1058	.0987	.0926
FC Ethanol (reformed)	.3487	.2789	.2325	.1992	.1743	.1550	.1395	.1268	.1162	.1073	.0996	.0930	.0872
FC Petrol (Reformed)	.2723	.2178	.1815	.1556	.1361	.1210	.1089	.0990	.0908	.0838	.0778	.0726	.0681
ICE Ethanol	9.866	7.893	6.577	5.638	4.933	4.385							
ICE RME	11.35	9.082	7.569	6.487	5.677	5.046							
ICE Diesel	7.256	5.805	4.837	4.146	3.628	3.225							
ICE Methanol	5.509	4.407	3.673	3.148	2.755	2.449							
ICE Methane	4.786	3.829	3.191	2.735	2.393	2.127							
ICE Petrol	4.605	3.684	3.070	2.631	2.302	2.047							
ICE Propane	4.443	3.555	2.962	2.539	2.222	1.975							

TABLE A.7 NOx EMISSIONS FOR DIFFERENT FUELS (Continued)

g NOx/kWh (Total):

Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC RME (Reformed)	3.830	3.064	2.553	2.189	1.915	1.702	1.532	1.393	1.277	1.178	1.094	1.021	.9575	
FC Bioethanol (Reformed)	4.744	3.795	3.163	2.711	2.372	2.108	1.898	1.725	1.581	1.460	1.355	1.265	1.186	
FC RME (Partial Oxidation)	4.044	3.235	2.696	2.311	2.022	1.797	1.618	1.471	1.348	1.244	1.155	1.078	1.011	
FC Bioethanol (Int. Reformed)	3.552	2.842	2.368	2.030	1.776	1.579	1.421	1.292	1.184	1.093	1.015	.9472	.8880	
FC RME (Int. Reformed)	2.794	2.235	1.863	1.597	1.397	1.242	1.118	1.016	.9314	.8597	.7983	.7451	.6985	
FC Biomethanol (Reformed)	2.303	1.842	1.535	1.316	1.151	1.024	.9212	.8374	.7677	.7086	.6580	.6141	.5757	
FC Biomethanol (Int. Reformed)	1.653	1.322	1.102	.9444	.8263	.7345	.6611	.6010	.5509	.5085	.4722	.4407	.4132	
FC Diesel (Reformed)	1.097	.8779	.7316	.6271	.5487	.4877	.4390	.3991	.3658	.3377	.3135	.2926	.2744	
FC Propane (Reformed)	1.095	.8756	.7297	.6254	.5473	.4864	.4378	.3980	.3648	.3368	.3127	.2919	.2736	
FC Petrol (Reformed)	.9683	.7747	.6456	.5533	.4842	.4304	.3873	.3521	.3228	.2980	.2767	.2582	.2421	
FC Petrol (Partial Oxidation)	.9281	.7425	.6187	.5303	.4640	.4125	.3712	.3375	.3094	.2856	.2652	.2475	.2320	
FC Propane (Partial Oxidation)	.9338	.7470	.6225	.5336	.4669	.4150	.3735	.3396	.3113	.2873	.2668	.2490	.2334	
H2 (Electrolysis)	.7969	.6375	.5313	.4554	.3985	.3542	.3188	.2898	.2656	.2452	.2277	.2125	.1992	
FC Diesel (Partial Oxidation)	.7258	.5806	.4839	.4147	.3629	.3226	.2903	.2639	.2419	.2233	.2074	.1935	.1814	
FC Methanol (Ref.)	.7034	.5627	.4689	.4019	.3517	.3126	.2813	.2558	.2345	.2164	.2010	.1876	.1758	
FC Methane (Reformed)	.6562	.5249	.4374	.3750	.3281	.2916	.2625	.2386	.2187	.2019	.1875	.1750	.1640	
FC Propane (Int. Reformed)	.6537	.5229	.4358	.3735	.3268	.2905	.2615	.2377	.2179	.2011	.1868	.1743	.1634	
FC Petrol (Int. Reformed)	.6328	.5062	.4219	.3616	.3164	.2812	.2531	.2301	.2109	.1947	.1808	.1687	.1582	
FC Diesel (Int. Reforming)	.4888	.3910	.3259	.2793	.2444	.2172	.1955	.1777	.1629	.1504	.1397	.1303	.1222	
FC Methane (Partial Oxidation)	.3140	.2512	.2093	.1794	.1570	.1396	.1256	.1142	.1047	.0966	.0897	.0837	.0785	
FC Methane (Int. Ref.)	.2355	.1884	.1570	.1346	.1178	.1047	.0942	.0856	.0785	.0725	.0673	.0628	.0589	
FC Methanol (Int. Reformed)	.1985	.1588	.1323	.1134	.0992	.0882	.0794	.0722	.0662	.0611	.0567	.0529	.0496	
Batt. Ch. (24 hrs)									2.953	2.726	2.531	2.363	2.215	2.085
Batt. Ch. (Night)									2.574	2.376	2.206	2.059	1.931	1.817
ICE Bioethanol	14.05	11.24	9.369	8.031	7.027	6.246								
ICE RME	15.55	12.44	10.36	8.884	7.774	6.910								
ICE Diesel	7.890	6.312	5.260	4.508	3.945	3.507								
ICE Biomethanol	7.386	5.909	4.924	4.221	3.693	3.283								
ICE Methanol	5.735	4.588	3.823	3.277	2.867	2.549								
ICE Propane	5.233	4.187	3.489	2.991	2.617	2.326								
ICE Methane	5.070	4.056	3.380	2.897	2.535	2.253								
ICE Petrol	5.372	4.298	3.581	3.070	2.686	2.388								

TABLE A.8 NITROUS OXIDE EMISSIONS FOR DIFFERENT FUELS

g N2O/kWh:														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Petrol (Reformed) (Use)	.0264	.0212	.0176	.0151	.0132	.0118	.0106	.0096	.0088	.0081	.0076	.0071	.0066	
FC Diesel (Reformed) (Use)	.0028	.0022	.0018	.0016	.0014	.0012	.0011	.0010	.0009	.0008	.0008	.0007	.0007	
Hydrogen (Electrolysis)	.0182	.0145	.0121	.0104	.0091	.0081	.0073	.0066	.0061	.0056	.0052	.0048	.0045	
Batt. Charge (24hrs)									.0673	.0622	.0577	.0539	.0505	.0475
Batt. Charge (Night)									.0427	.0394	.0366	.0341	.032	.0301
ICE Petrol (Use)	.3207	.2566	.2138	.1833	.1603	.1425								
ICE Diesel (Use)	.0357	.0285	.0238	.0204	.0178	.0159								

TABLE A.9 SULPHUR DIOXIDE EMISSIONS FOR DIFERENT FUELS

g SO2/kWh (Fuel Production):

Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Bioethanol (Ref.)	3.391	2.713	2.261	1.938	1.696	1.507	1.357	1.233	1.130	1.043	.9689	.9043	.8478	
FC Bioethanol (Int. Ref.)	3.083	2.466	2.055	1.762	1.541	1.370	1.233	1.121	1.028	.9486	.8809	.8221	.7707	
FC RME (Partial Oxidation)	2.555	2.044	1.703	1.460	1.277	1.135	1.022	.9290	.8516	.7861	.7299	.6813	.6387	
H2 (Electrolysis)	2.439	1.952	1.626	1.394	1.220	1.084	.9758	.8870	.8131	.7506	.6970	.6505	.6098	
FC RME (Reformed)	1.942	1.553	1.294	1.109	.9708	.8629	.7766	.7060	.6472	.5974	.5547	.5178	.4854	
FC RME (Int. Reformed)	1.765	1.412	1.177	1.009	.8825	.7845	.7060	.6418	.5884	.5431	.5043	.4707	.4413	
FC Petrol (Partial Oxidation)	1.588	1.270	1.059	.9075	.7940	.7058	.6352	.5775	.5294	.4886	.4537	.4235	.3970	
FC Petrol (Reformed)	1.191	.9528	.7940	.6806	.5955	.5294	.4764	.4331	.3970	.3665	.3403	.3176	.2978	
FC Petrol (Int. Reformed)	1.083	.8662	.7218	.6187	.5414	.4812	.4331	.3937	.3609	.3332	.3094	.2887	.2707	
FC Diesel (Partial Oxidation)	1.034	.8274	.6895	.5910	.5171	.4597	.4137	.3761	.3448	.3182	.2955	.2758	.2586	
FC Propane (Partial Oxidation)	.9693	.7754	.6462	.5539	.4846	.4308	.3877	.3525	.3231	.2982	.2769	.2585	.2423	
FC Diesel (Reformed)	.7662	.6130	.5108	.4378	.3831	.3405	.3065	.2786	.2554	.2358	.2189	.2043	.1915	
FC Propane (Reformed)	.7463	.5971	.4975	.4265	.3732	.3317	.2985	.2714	.2488	.2296	.2132	.1990	.1866	
FC Diesel (Int. Reformed)	.6965	.5572	.4644	.3980	.3483	.3096	.2786	.2533	.2322	.2143	.1990	.1857	.1741	
FC Propane (Int. Reformed)	.6785	.5428	.4523	.3877	.3392	.3015	.2714	.2467	.2262	.2088	.1939	.1809	.1696	
FC Methane (Partial oxidation)	.5659	.4527	.3773	.3234	.2830	.2515	.2264	.2058	.1886	.1741	.1617	.1509	.1415	
FC Biomethanol (Ref.)	.4704	.3763	.3136	.2688	.2352	.2090	.1881	.1710	.1568	.1447	.1344	.1254	.1176	
FC Methane (Reformed)	.4666	.3733	.3111	.2666	.2333	.2074	.1866	.1697	.1555	.1436	.1333	.1244	.1166	
FC Biomethanol (Int. Reformed)	.4276	.3421	.2851	.2443	.2138	.1900	.1710	.1555	.1425	.1316	.1222	.1140	.1069	
FC Methane (Int. Reformed)	.4242	.3393	.2828	.2424	.2121	.1885	.1697	.1542	.1414	.1305	.1212	.1131	.1060	
Battery (24 hrs ch.)									9.04	8.345	7.749	7.232	6.78	6.381
Battery (Night ch.)									7.193	6.64	6.166	5.755	5.395	5.078
ICE Ethanol	3.635	2.908	2.423	2.077	1.817	1.615								
ICE RME	2.649	2.120	1.766	1.514	1.325	1.178								
ICE Petrol	1.313	1.050	.8753	.7502	.6565	.5835								
ICE Diesel	.9030	.7224	.6020	.5160	.4515	.4013								
ICE Propane	.8200	.6560	.5467	.4686	.4100	.3644								
ICE Biomethanol	.4857	.3885	.3238	.2775	.2428	.2159								
ICE Methane	.5637	.4510	.3758	.3221	.2819	.2505								

TABLE A.10 PM EMISSIONS FOR DIFFERENT FUEL

gPM/kWh (Use): Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC Diesel (Reformed)	.0929	.0743	.0619	.0531	.0464	.0413	.0372	.0338	.0310	.0286	.0265	.0248	.0232
FC RME (Reformed)	.0743	.0595	.0496	.0425	.0372	.0330	.0297	.0270	.0248	.0229	.0212	.0198	.0186
FC Methanol (Reformed)	.0406	.0324	.0270	.0232	.0203	.0180	.0162	.0147	.0135	.0125	.0116	.0108	.0101
FC Ethanol (Reformed)	.0292	.0233	.0194	.0167	.0146	.0130	.0117	.0106	.0097	.0090	.0083	.0078	.0073
FC Propane (Reformed)	.0220	.0176	.0147	.0126	.0110	.0098	.0088	.0080	.0073	.0068	.0063	.0059	.0055
FC Petrol (Reformed)	.0237	.0190	.0158	.0136	.0119	.0105	.0095	.0086	.0079	.0073	.0068	.0063	.0059
FC Methane (Reformed)	.0122	.0098	.0082	.0070	.0061	.0054	.0049	.0045	.0041	.0038	.0035	.0033	.0031
ICE Diesel	1.204	.9633	.8028	.6881	.6021	.5352							
ICE RME	1.116	.8927	.7439	.6377	.5580	.4960							
ICE Methanol	.4606	.3685	.3071	.2632	.2303	.2047							
ICE Ethanol	.3437	.2750	.2291	.1964	.1718	.1528							
ICE Propane	.2658	.2127	.1772	.1519	.1329	.1181							
ICE Petrol	.2878	.2302	.1919	.1645	.1439	.1279							
ICE Methane	.1475	.1180	.0984	.0843	.0738	.0656							

TABLE A.10 PM EMISSIONS FOR DIFFERENT FUELS (Continued)

g PM/kWh (Total):														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC RME (Partial Oxidation)	.5999	.4799	.3999	.3428	.3000	.2666	.2400	.2181	.2000	.1846	.1714	.1600	.1500	
FC Bioethanol (Reformed)	.6537	.5230	.4358	.3735	.3268	.2905	.2615	.2377	.2179	.2011	.1868	.1743	.1634	
FC RME (Reformed)	.5303	.4242	.3535	.3030	.2651	.2357	.2121	.1928	.1768	.1632	.1515	.1414	.1326	
FC Bioethanol (Int. Reformed)	.5678	.4542	.3785	.3244	.2839	.2523	.2271	.2065	.1893	.1747	.1622	.1514	.1419	
FC RME (Int. Reformed)	.4145	.3316	.2763	.2368	.2072	.1842	.1658	.1507	.1382	.1275	.1184	.1105	.1036	
FC Biomethanol (Reformed)	.1834	.1468	.1223	.1048	.0917	.0815	.0734	.0667	.0611	.0564	.0524	.0489	.0459	
FC Biomethanol (Int. Reformed)	.1299	.1039	.0866	.0742	.0649	.0577	.0519	.0472	.0433	.0400	.0371	.0346	.0325	
FC Diesel (Reformed)	.0946	.0757	.0630	.0540	.0473	.0420	.0378	.0344	.0315	.0291	.0270	.0252	.0236	
H2 (Electrolysis)	.0585	.0468	.0390	.0334	.0292	.0260	.0234	.0213	.0195	.0180	.0167	.0156	.0146	
FC Propane (Reformed)	.0311	.0249	.0207	.0178	.0155	.0138	.0124	.0113	.0104	.0096	.0089	.0083	.0078	
FC Petrol (Reformed)	.0255	.0204	.0170	.0145	.0127	.0113	.0102	.0093	.0085	.0078	.0073	.0068	.0064	
FC Methane (Reformed)	.0122	.0098	.0082	.0070	.0061	.0054	.0049	.0045	.0041	.0038	.0035	.0033	.0031	
FC Propane (Partial Oxidation)	.0118	.0095	.0079	.0068	.0059	.0053	.0047	.0043	.0039	.0036	.0034	.0032	.0030	
FC Propane (Int. Reformed)	.0083	.0066	.0055	.0047	.0041	.0037	.0033	.0030	.0028	.0025	.0024	.0022	.0021	
FC Petrol (Partial Oxidation)	.0023	.0018	.0015	.0013	.0011	.0010	.0009	.0008	.0008	.0007	.0007	.0006	.0006	
FC Diesel (Partial Oxidation)	.0023	.0018	.0015	.0013	.0011	.0010	.0009	.0008	.0008	.0007	.0006	.0006	.0006	
FC Petrol (Int. Reforming)	.0016	.0012	.0010	.0009	.0008	.0007	.0006	.0006	.0005	.0005	.0004	.0004	.0004	
FC Diesel (Int. Reformed)	.0015	.0012	.0010	.0009	.0008	.0007	.0006	.0006	.0005	.0005	.0004	.0004	.0004	
Battery Charge (24hrs)									.2167	.2	.1857	.1733	.1625	.1529
Battery Charge (Night)									.1567	.1446	.1343	.1253	.1175	.1106
ICE Diesel	1.206	.9649	.8041	.6892	.6031	.5361								
ICE RME	1.738	1.390	1.159	.9932	.8690	.7725								
ICE Bioethanol	1.013	.8104	.6754	.5789	.5065	.4502								
ICE Biomethanol	.6082	.4865	.4054	.3475	.3041	.2703								
ICE Petrol	.2897	.2318	.1931	.1655	.1448	.1288								

TABLE A.11 CARBON DIOXIDE EMISSIONS FOR MANUFACTURE OF HYDROGEN BY ELECTROLYSIS

Fuel Cell Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
Current Mix of Power Stations:													
gCO2/kWh	224.3	179.4	149.5	128.2	112.1	99.68	89.71	81.56	74.76	69.01	64.08	59.81	56.07
Geothermal Energy:													
gCO2/kWh	22.71	18.17	15.14	12.98	1.135	10.09	9.083	8.258	7.569	6.987	6.488	6.056	5.677
Wind Energy:													
gCO2/kWh	2.843	2.275	1.896	1.625	1.422	1.264	1.137	1.034	.9478	.8748	.8124	.7582	.7108
Nuclear Energy:													
gCO2/kWh	2.183	1.747	1.455	1.248	1.092	.9703	.8733	.7939	.7277	.6717	.6238	.5822	.5458
Photovoltaic Energy:													
gCO2/kWh	2.075	1.660	1.383	1.186	1.037	.9221	.8299	.7545	.6916	.6384	.5928	.5533	.5187
Solar Thermal Energy:													
gCO2/kWh	1.383	1.107	.9221	.7904	.6916	.6148	.5533	.5030	.4611	.4256	.3952	.3689	.3458
Large Hydro-electric Energy:													
gCO2/kWh	1.191	.9529	.7941	.6806	.5955	.5294	.4764	.4331	.3970	.3665	.3403	.3176	.2978

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TABLE A.12 LIFETIME CARBON DIOXIDE EMISSIONS FOR URBAN BUSES

Lifetime kg CO2/kW (Use): Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC RME (Partial Oxidation)	5461.	4369.	3640.	3120.	2730.	2427.	2184.	1986.	1820.	1680.	1560.	1456.	1365.
FC Diesel (Partial Oxidation)	5295.	4236.	3530.	3026.	2648.	2353.	2118.	1926.	1765.	1629.	1513.	1412.	1324.
FC Petrol (Partial Oxidation)	5097.	4077.	3398.	2912.	2548.	2265.	2039.	1853.	1699.	1568.	1456.	1359.	1274.
FC Propane (Partial Oxidation)	4681.	3745.	3120.	2675.	2340.	2080.	1872.	1702.	1560.	1440.	1337.	1248.	1170.
FC RME (Steam Reformed)	4152.	3322.	2768.	2373.	2076.	1845.	1661.	1510.	1384.	1278.	1186.	1107.	1038.
FC Ethanol (Steam Reformed)	4007.	3206.	2671.	2290.	2004.	1781.	1603.	1457.	1336.	1233.	1145.	1069.	1002.
FC Methanol (Steam Reformed)	4000.	3200.	2667.	2286.	2000.	1778.	1600.	1455.	1333.	1231.	1143.	1067.	1000.
FC Diesel (Steam Reformed)	3932.	3145.	2621.	2247.	1966.	1747.	1573.	1430.	1311.	1210.	1123.	1048.	983.0
FC Petrol (Steam Reformed)	3816.	3053.	2544.	2180.	1908.	1696.	1526.	1388.	1272.	1174.	1090.	1018.	953.9
FC RME (Internally Reformed)	3773.	3018.	2515.	2156.	1886.	1677.	1509.	1372.	1258.	1161.	1078.	1006.	943.2
FC Methane (Partial Oxidation)	3641.	2912.	2427.	2080.	1820.	1618.	1456.	1324.	1214.	1120.	1040.	970.8	910.1
FC Ethanol (Internally Reformed)	3642.	2914.	2428.	2081.	1821.	1619.	1457.	1324.	1214.	1121.	1041.	971.2	910.5
FC Methanol (Internally Reformed)	3641.	2912.	2427.	2080.	1820.	1618.	1456.	1324.	1214.	1120.	1040.	970.8	910.1
FC Propane (Steam Reformed)	3617.	2894.	2412.	2067.	1809.	1608.	1447.	1315.	1206.	1113.	1034.	964.6	904.3
FC Diesel (Internally Reformed)	3566.	2853.	2377.	2038.	1783.	1585.	1426.	1297.	1189.	1097.	1019.	951.0	891.6
FC Petrol (Internally Reformed)	3475.	2780.	2317.	1986.	1738.	1544.	1390.	1264.	1158.	1069.	992.9	926.7	868.8
FC Propane (Internally Reformed)	3289.	2631.	2193.	1879.	1644.	1462.	1316.	1196.	1096.	1012.	939.7	877.1	822.2
FC Methane (Steam Reformed)	3004.	2403.	2003.	1717.	1502.	1335.	1202.	1092.	1001.	924.3	858.3	801.1	751.0
FC Methane (Internally Reformed)	2730.	2184.	1820.	1560.	1365.	1214.	1092.	992.9	910.1	840.1	780.1	728.1	682.6
ICE Diesel	4739.	3791.	3160.	2708.	2370.	2106.							
ICE RME	5691.	4553.	3794.	3252.	2845.	2529.							
ICE Ethanol	4297.	3438.	2865.	2456.	2149.	1910.							
ICE Petrol	4131.	3305.	2754.	2361.	2066.	1836.							
ICE Methanol	4139.	3312.	2760.	2365.	2070.	1840.							
ICE Propane	3967.	3174.	2645.	2267.	1984.	1763.							
ICE Methane	3299.	2639.	2199.	1885.	1649.	1466.							

TABLE A.12 LIFETIME CARBON DIOXIDE EMISSIONS FOR URBAN BUSES (Continued)

Lifetime kgCO2/kW (Total): Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC RME (Partial Oxidation)	6931.	5545.	4621.	3961.	3465.	3080.	2772.	2520.	2310.	2133.	1980.	1848.	1733.	
FCPetrol (Partial Oxidation)	5883.	4707.	3922.	3362.	2942.	2615.	2353.	2139.	1961.	1810.	1681.	1569.	1471.	
FC Diesel (Partial Oxidation)	5816.	4653.	3877.	3323.	2908.	2585.	2326.	2115.	1939.	1790.	1662.	1551.	1454.	
FC Biomethanol (Steam Reformed)	6674.	5339.	4450.	3814.	3337.	2966.	2670.	2427.	2225.	2054.	1907.	1780.	1669.	
FC RME (Steam Reformed)	5269.	4215.	3513.	3011.	2635.	2342.	2108.	1916.	1756.	1621.	1506.	1405.	1317.	
FC Bioethanol (Steam Reformed)	5469.	4376.	3646.	3125.	2735.	2431.	2188.	1989.	1823.	1683.	1563.	1459.	1367.	
FC Propane (Partial Oxidation)	5280.	4224.	3520.	3017.	2640.	2346.	2112.	1920.	1760.	1624.	1508.	1408.	1320.	
FC Biomethanol (Internally Reformed)	5268.	4214.	3512.	3010.	2634.	2341.	2107.	1915.	1756.	1621.	1505.	1405.	1317.	
FC RME (Internally Reformed)	4789.	3831.	3193.	2736.	2394.	2128.	1916.	1741.	1596.	1473.	1368.	1277.	1197.	
FC Bioethanol (Internally Reformed)	4971.	3977.	3314.	2841.	2486.	2209.	1989.	1808.	1657.	1530.	1420.	1326.	1243.	
FC Methanol (Steam Reformed)	4463.	3571.	2976.	2550.	2232.	1984.	1785.	1623.	1488.	1373.	1275.	1190.	1116.	
FC Petrol (Steam Reformed)	4406.	3525.	2937.	2518.	2203.	1958.	1762.	1602.	1469.	1356.	1259.	1175.	1101.	
FC Diesel (Steam Reformed)	4318.	3455.	2879.	2468.	2159.	1919.	1727.	1570.	1439.	1329.	1234.	1152.	1080.	
FC Propane (Steam Reformed)	4078.	3263.	2719.	2331.	2039.	1813.	1631.	1483.	1359.	1255.	1165.	1088.	1020.	
FC Methane (Partial Oxidation)	3994.	3195.	2663.	2282.	1997.	1775.	1598.	1452.	1331.	1229.	1141.	1065.	998.6	
FC Petrol (Internally Reformed)	4262.	3409.	2841.	2435.	2131.	1894.	1705.	1550.	1421.	1311.	1218.	1136.	1065.	
FC Diesel (Internally Reformed)	4087.	3270.	2725.	2335.	2043.	1816.	1635.	1486.	1362.	1258.	1168.	1090.	1022.	
FC Methanol (Internally Reformed)	4061.	3249.	2708.	2321.	2031.	1805.	1625.	1477.	1354.	1250.	1160.	1083.	1015.	
FC Propane (Internally Reformed)	3708.	2967.	2472.	2119.	1854.	1648.	1483.	1348.	1236.	1141.	1059.	988.9	927.1	
FC Methane (Steam Reformed)	3296.	2637.	2197.	1883.	1648.	1465.	1318.	1199.	1099.	1014.	941.7	878.9	824.0	
FC Methane (Internally Reformed)	3084.	2467.	2056.	1762.	1542.	1371.	1234.	1122.	1028.	949.0	881.2	822.5	771.1	
Hydrogen (Electrolysis)	970.2	776.2	646.8	554.4	485.1	431.2	388.1	352.8	323.4	298.5	277.2	258.7	242.6	
Batt. CHarge (24hrs)									3596.	3319.	3082.	2877.	2697.	2538.
Batt. Charge (Night)									3149.	2907.	2699.	2519.	2362.	2223.
ICE Biomethanol	5988.	4790.	3992.	3421.	2994.	2661.								
ICE RME	7216.	5772.	4810.	4123.	3608.	3207.								
ICE Bioethanol	5864.	4691.	3909.	3351.	2932.	2606.								
ICE Diesel	5195.	4156.	3463.	2968.	2597.	2309.								
ICE Petrol	4782.	3825.	3188.	2732.	2391.	2125.								
ICE Methanol	4618.	3694.	3078.	2639.	2309.	2052.								
ICE Propane	4474.	3579.	2983.	2557.	2237.	1988.								
ICE Methane	3619.	2895.	2412.	2068.	1809.	1608.								

TABLE A.13 LIFETIME CARBON MONOXIDE EMISSIONS FOR URBAN BUSES

kg CO/kW (Use):													
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC Petrol (Reformed)	5.040	4.032	3.360	2.880	2.520	2.240	2.016	1.833	1.680	1.551	1.440	1.344	1.260
FC Bioethanol (Reformed)	4.516	3.613	3.011	2.581	2.258	2.007	1.806	1.642	1.505	1.390	1.290	1.204	1.129
FC RME (Reformed)	3.184	2.547	2.123	1.819	1.592	1.415	1.274	1.158	1.061	.9796	.9097	.8490	.7960
FC Diesel (Reformed)	2.523	2.018	1.682	1.442	1.261	1.121	1.009	.9174	.8410	.7763	.7208	.6728	.6307
FC Biomethanol (Reformed)	1.617	1.293	1.078	.9239	.8084	.7186	.6467	.5879	.5389	.4975	.4619	.4312	.4042
FC Methane (Reformed)	.4976	.3981	.3317	.2844	.2488	.2212	.1990	.1810	.1659	.1531	.1422	.1327	.1244
FC Propane (Reformed)	.4725	.3780	.3150	.2700	.2363	.2100	.1890	.1718	.1575	.1454	.1350	.1260	.1181
Hydrogen (Electrolysis)	.2716	.2173	.1811	.1552	.1358	.1207	.1087	.0988	.0905	.0836	.0776	.0724	.0679
ICE Petrol	61.11	48.89	40.74	34.92	30.56	27.16							
ICE Ethanol	53.10	42.48	35.40	30.34	26.55	23.60							
ICE Diesel	32.71	26.16	21.80	18.69	16.35	14.54							
ICE RME	29.37	23.50	19.58	16.78	14.69	13.05							
ICE Methanol	18.36	14.69	12.24	10.49	9.182	8.162							
ICE Methane	5.998	4.798	3.998	3.427	2.999	2.666							
ICE Propane	5.687	4.549	3.791	3.249	2.843	2.527							

TABLE A.13 LIFETIME CARBON MONOXIDE EMISSIONS FOR URBAN BUSES (Continued)

Lifetime kg CO/kW Total):														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Bioethanol (Reformed)	12.64	10.12	8.429	7.225	6.322	5.620	5.058	4.598	4.215	3.891	3.613	3.372	3.161	
FC RME (Reformed)	8.153	6.522	5.435	4.659	4.076	3.623	3.261	2.965	2.718	2.508	2.329	2.174	2.038	
FC RME (Partial Oxidation)	6.538	5.230	4.359	3.736	3.269	2.906	2.615	2.377	2.179	2.012	1.868	1.743	1.634	
FC Bioethanol (Int. Reformed)	7.370	5.896	4.913	4.211	3.685	3.276	2.948	2.680	2.457	2.268	2.106	1.965	1.842	
FC Petrol (Reformed)	5.326	4.261	3.551	3.044	2.663	2.367	2.130	1.937	1.775	1.639	1.522	1.420	1.332	
FC RME (Int. Reformed)	4.517	3.614	3.011	2.581	2.258	2.008	1.807	1.643	1.506	1.390	1.291	1.205	1.129	
FC Biomethanol (Reformed)	3.191	2.553	2.128	1.824	1.596	1.418	1.277	1.160	1.064	.9819	.9118	.8510	.7978	
FC Diesel (Reformed)	2.758	2.206	1.839	1.576	1.379	1.226	1.103	1.003	.9194	.8487	.7880	.7355	.6895	
FC Methanol (Reformed)	1.881	1.505	1.254	1.075	.9407	.8362	.7526	.6842	.6271	.5789	.5376	.5017	.4704	
FC Propane (Reformed)	.8260	.6608	.5506	.4720	.4130	.3671	.3304	.3004	.2753	.2541	.2360	.2203	.2065	
FC Methane (Reformed)	.6132	.4905	.4088	.3504	.3066	.2725	.2453	.2230	.2044	.1887	.1752	.1635	.1533	
FC Propane (Partial Oxidation)	.4570	.3656	.3047	.2612	.2285	.2031	.1828	.1662	.1523	.1406	.1306	.1219	.1143	
FC Petrol (Partial Oxidation)	.3819	.3074	.2561	.2196	.1921	.1708	.1537	.1397	.1281	.1182	.1098	.1025	.0961	
FC Propane (Int. Reformed)	.3199	.2559	.2133	.1828	.1600	.1422	.1280	.1163	.1066	.0984	.0914	.0853	.0800	
FC Diesel (Partial Oxidation)	.3175	.2540	.2117	.1814	.1588	.1411	.1270	.1155	.1058	.0977	.0907	.0847	.0794	
Hydrogen (Electrolysis)	.2716	.2173	.1811	.1552	.1358	.1207	.1087	.0988	.0905	.0836	.0776	.0724	.0679	
FC Petrol (Int. Reformed)	.2604	.2083	.1736	.1488	.1302	.1157	.1042	.0947	.0868	.0801	.0744	.0694	.0651	
FC Methanol (Int. Reformed)	.2406	.1924	.1604	.1375	.1203	.1069	.0962	.0875	.0802	.0740	.0687	.0641	.0601	
FC Diesel (Int. Reformed)	.2139	.1711	.1426	.1222	.1069	.0951	.0856	.0778	.0713	.0658	.0611	.0570	.0535	
FC Methane (Partial Oxidation)	.1401	.1120	.0934	.0800	.0700	.0622	.0560	.0509	.0467	.0431	.0400	.0373	.0350	
FC Methane (Int. Reformed)	.1050	.0840	.0700	.0600	.0525	.0467	.0420	.0382	.0350	.0323	.0300	.0280	.0263	
Batt. Charge (24hrs)									1.007	.9292	.8629	.8053	.755	.7106
Batt. Charge (Night)									1	.9231	.8571	.8	.75	.7059
Petrol ICE	61.43	49.14	40.95	35.10	30.71	27.30								
Bioethanol ICE	61.79	49.43	41.20	35.31	30.90	27.46								
Diesel ICE	32.98	26.39	21.99	18.85	16.49	14.66								
RME ICE	36.15	28.92	24.10	20.66	18.08	16.07								
Biomethanol ICE	19.99	15.99	13.33	11.42	9.995	8.884								
Methanol ICE	18.64	14.91	12.43	10.65	9.319	8.283								
Methane ICE	6.124	4.899	4.083	3.500	3.062	2.722								
Propane ICE	6.073	4.859	4.049	3.470	3.037	2.699								

TABLE A.14 LIFETIME METHANE EMISSIONS FOR URBAN BUSES

kg Methane/kW (Use): Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC Methane (Reformed)	1.324	1.059	.8825	.7564	.6618	.5883	.5295	.4813	.4412	.4073	.3782	.3530	.3309
FC Propane (Reformed)	.0660	.0528	.0440	.0377	.0330	.0293	.0264	.0240	.0220	.0203	.0188	.0176	.0165
FC Methanol (Reformed)	.0530	.0424	.0353	.0303	.0265	.0236	.0212	.0193	.0177	.0163	.0151	.0141	.0133
FC Petrol (Reformed)	.0353	.0282	.0235	.0202	.0176	.0157	.0141	.0128	.0118	.0109	.0101	.0094	.0088
FC Ethanol (Reformed)	.0381	.0305	.0254	.0218	.0191	.0169	.0152	.0139	.0127	.0117	.0109	.0102	.0095
FC Diesel (Reformed)	.0218	.0174	.0145	.0125	.0109	.0097	.0087	.0079	.0073	.0067	.0062	.0058	.0054
ICE Methane	17.99	14.39	12.00	10.28	8.996	7.997							
ICE Propane	.7935	.6348	.5290	.4534	.3967	.3527							
ICE Petrol	.4276	.3421	.2851	.2443	.2138	.1900							
ICE Diesel	.2825	.2260	.1883	.1614	.1412	.1255							

TABLE A.14 LIFETIME METHANE EMISSIONS FOR URBAN BUSES (Continued)

kg Methane/kW (Total):														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Methane (Partial Oxidation)	16.16	12.92	10.77	9.232	8.078	7.180	6.462	5.875	5.385	4.971	4.616	4.308	4.039	
FC Methane (Reformed)	14.58	11.67	9.721	8.332	7.291	6.481	5.833	5.302	4.860	4.487	4.166	3.888	3.645	
FC Methane (Int. Ref.)	12.12	9.694	8.078	6.924	6.058	5.385	4.847	4.406	4.039	3.728	3.462	3.231	3.029	
Hydrogen (Electrolysis)	2.874	2.299	1.916	1.642	1.437	1.277	1.149	1.045	.9578	.8842	.8210	.7663	.7184	
FC Propane (Partial Oxidation)	1.347	1.078	.8983	.7700	.6737	.5989	.5390	.4900	.4492	.4146	.3850	.3593	.3369	
FC Petrol (Partial Oxidation)	1.199	.9590	.7992	.6850	.5994	.5328	.4795	.4359	.3996	.3689	.3425	.3197	.2997	
FC Diesel (Partial Oxidation)	1.111	.8884	.7403	.6346	.5553	.4936	.4442	.4038	.3702	.3417	.3173	.2961	.2776	
FC Propane (Reformed)	1.102	.8819	.7349	.6299	.5512	.4899	.4410	.4009	.3675	.3392	.3150	.2940	.2756	
FC Petrol (Reformed)	.9290	.7432	.6193	.5308	.4645	.4129	.3716	.3378	.3097	.2858	.2654	.2477	.2322	
FC Propane (Int. Ref.)	.9432	.7546	.6288	.5390	.4716	.4192	.3773	.3430	.3144	.2902	.2695	.2515	.2358	
FC Diesel (Reformed)	.8395	.6716	.5597	.4797	.4198	.3731	.3358	.3053	.2798	.2583	.2399	.2239	.2099	
FC Petrol (Int. Ref.)	.7216	.5773	.4810	.4123	.3608	.3207	.2886	.2624	.2405	.2220	.2062	.1924	.1804	
FC Diesel (Int. Ref.)	.7479	.5983	.4986	.4274	.3739	.3324	.2992	.2720	.2493	.2301	.2137	.1994	.1870	
FC Methanol (Reformed)	6.132	6.095	6.070	6.053	6.039	6.029	6.021	6.014	6.008	6.004	6.000	5.996	5.993	
FC Methanol (Int. Ref.)	5.579	5.545	5.522	5.505	5.493	5.483	5.475	5.469	5.464	5.459	5.456	5.452	5.449	
FC Biomethanol (Reformed)	.0530	.0424	.0353	.0303	.0265	.0236	.0212	.0193	.0177	.0163	.0151	.0141	.0133	
FC Bioethanol (Reformed)	.0381	.0305	.0254	.0218	.0191	.0169	.0152	.0139	.0127	.0117	.0109	.0102	.0095	
Batt. Charge (24hrs)									10.65	9.830	9.128	8.519	7.987	7.517
Batt. Charge (Night)									9.998	9.229	8.570	7.998	7.498	7.057
ICE Methane	32.52	26.02	21.68	18.58	16.26	14.45								
ICE Propane	1.927	1.541	1.285	1.101	.9634	.8563								
ICE Petrol	1.297	1.038	.8649	.7413	.6487	.5766								
ICE Diesel	1.246	.9969	.8308	.7121	.6231	.5538								
ICE Methanol	11.20	11.05	10.95	10.88	10.83	10.78								
ICE Biomethanol	.6021	.4817	.4014	.3441	.3011	.2676								
ICE Bioethanol	.4493	.3594	.2995	.2567	.2246	.1997								

TABLE A.15 LIFETIME NMVOC EMISSIONS FOR URBAN BUSES

kg NMVOC/kW (Use): Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC Reformed Petrol	.6759	.5407	.4506	.3862	.3379	.3004	.2704	.2458	.2253	.2080	.1931	.1802	.1690
FC Methanol (Reformed)	.6096	.4877	.4064	.3484	.3048	.2709	.2438	.2217	.2032	.1876	.1742	.1626	.1524
FC Diesel (Reformed)	.4690	.3752	.3127	.2680	.2345	.2085	.1876	.1706	.1563	.1443	.1340	.1251	.1173
FC RME (Reformed)	.4579	.3663	.3053	.2617	.2290	.2035	.1832	.1665	.1526	.1409	.1308	.1221	.1145
FC Ethanol (Reformed)	.4382	.3506	.2922	.2504	.2191	.1948	.1753	.1594	.1461	.1348	.1252	.1169	.1096
FC Propane (Reformed)	.3283	.2626	.2188	.1876	.1641	.1459	.1313	.1194	.1094	.1010	.0938	.0875	.0821
FC Methane (Reformed)	.1294	.1035	.0863	.0739	.0647	.0575	.0518	.0470	.0431	.0398	.0370	.0345	.0323
ICE RME	12.59	10.08	8.396	7.197	6.297	5.597							
ICE Petrol	8.196	6.556	5.464	4.683	4.098	3.642							
ICE Ethanol	7.638	6.110	5.092	4.364	3.819	3.394							
ICE Methanol	6.924	5.539	4.616	3.957	3.462	3.077							
ICE Diesel	6.080	4.864	4.054	3.474	3.040	2.702							
ICE Propane	3.967	3.174	2.645	2.267	1.984	1.763							
ICE Methane	1.559	1.248	1.040	.8911	.7797	.6931							

TABLE A.15 LIFETIME NMVOC EMISSIONS FOR URBAN BUSES (Continued)

kg NMVOC/kW (Total):														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Biomethanol (Reformed)	13.93	11.14	9.284	7.958	6.963	6.190	5.571	5.064	4.642	4.285	3.979	3.714	3.482	
FC Biomethanol (Int. Ref.)	12.11	9.685	8.071	6.918	6.053	5.381	4.842	4.402	4.035	3.725	3.459	3.228	3.027	
FC Petrol (Partial Oxidation)	16.18	12.94	10.79	9.245	8.089	7.190	6.471	5.883	5.393	4.978	4.622	4.314	4.045	
FC Petrol (Reformed)	12.81	10.25	8.540	7.320	6.405	5.693	5.124	4.658	4.270	3.941	3.660	3.416	3.202	
FC Petrol (Int. Ref.)	11.03	8.825	7.354	6.303	5.515	4.903	4.412	4.011	3.677	3.394	3.152	2.942	2.758	
FC Bioethanol (Reformed)	8.240	6.592	5.493	4.708	4.120	3.662	3.296	2.996	2.747	2.535	2.354	2.197	2.060	
FC Diesel (Partial Oxidation)	6.925	5.540	4.617	3.957	3.463	3.078	2.770	2.518	2.308	2.131	1.979	1.847	1.731	
FC Bioethanol (Int. Ref.)	7.092	5.674	4.728	4.053	3.546	3.152	2.837	2.579	2.364	2.182	2.026	1.891	1.773	
FC RME (Partial Oxidation)	5.598	4.478	3.732	3.199	2.799	2.488	2.239	2.036	1.866	1.722	1.599	1.493	1.399	
FC Diesel (Reformed)	5.599	4.479	3.733	3.200	2.800	2.489	2.240	2.036	1.866	1.723	1.600	1.493	1.400	
Propane (Partial Oxidation)	5.059	4.047	3.373	2.891	2.530	2.248	2.024	1.840	1.686	1.557	1.445	1.349	1.265	
FC Diesel (Int. Ref.)	4.664	3.731	3.109	2.665	2.332	2.073	1.866	1.696	1.555	1.435	1.333	1.244	1.166	
FC RME (Reformed)	4.254	3.403	2.836	2.431	2.127	1.891	1.702	1.547	1.418	1.309	1.215	1.134	1.064	
FC Propane (Reformed)	4.224	3.379	2.816	2.414	2.112	1.877	1.689	1.536	1.408	1.300	1.207	1.126	1.056	
FC RME (Int. Reformed)	3.867	3.094	2.578	2.210	1.934	1.719	1.547	1.406	1.289	1.190	1.105	1.031	.9668	
FC Propane (Int. Ref.)	3.541	2.833	2.361	2.024	1.771	1.574	1.417	1.288	1.180	1.090	1.012	.9443	.8853	
FC Methane (Partial Oxidation)	2.705	2.164	1.804	1.546	1.353	1.202	1.082	.9838	.9018	.8324	.7730	.7214	.6763	
FC Methane (Reformed)	2.361	1.889	1.574	1.349	1.181	1.049	.9445	.8586	.7871	.7265	.6747	.6297	.5903	
FC Methane (Int. Ref.)	2.029	1.623	1.353	1.159	1.014	.9018	.8116	.7378	.6763	.6243	.5797	.5411	.5072	
H2 (Electrolysis)	.0492	.0393	.0328	.0281	.0246	.0219	.0197	.0179	.0164	.0151	.0140	.0131	.0123	
Batt. Charge (24hrs)									.1822	.1682	.1562	.1458	.1367	.1286
Batt. Charge (Night)									.1244	.1149	.1067	.0996	.0933	.0878
ICE Biomethanol	13.18	10.55	8.788	7.532	6.591	5.858								
ICE Petrol	20.00	16.00	13.34	11.43	10.00	8.891								
ICE Bioethanol	16.00	12.80	10.67	9.142	7.999	7.111								
ICE Diesel	12.13	9.701	8.084	6.929	6.063	5.390								
ICE RME	12.88	10.26	8.522	7.289	6.368	5.653								
ICE Propane	8.247	6.598	5.498	4.713	4.124	3.665								
ICE Ethanol	7.812	6.222	5.169	4.421	3.862	3.429								
ICE Methane	7.697	6.158	5.131	4.398	3.848	3.421								

TABLE A.16 LIFETIME NOx EMISSIONS FOR URBAN BUSES

kg NOx/kW (Use)													
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC RME (Reformed)	2.521	2.017	1.681	1.441	1.261	1.121	1.008	.9168	.8404	.7758	.7204	.6723	.6303
FC Bioethanol (Reformed)	2.789	2.232	1.860	1.594	1.395	1.240	1.116	1.014	.9298	.8583	.7970	.7439	.6974
FC Diesel (Reformed)	1.866	1.493	1.244	1.066	.9329	.8292	.7463	.6785	.6219	.5741	.5331	.4975	.4664
FC Methanol (Reformed)	1.617	1.293	1.078	.9239	.8084	.7186	.6467	.5879	.5389	.4975	.4619	.4312	.4042
FC Methane (Reformed)	1.324	1.059	.8825	.7564	.6618	.5883	.5295	.4813	.4412	.4073	.3782	.3530	.3309
FC Propane (Reformed)	1.234	.9875	.8229	.7054	.6172	.5486	.4937	.4489	.4115	.3798	.3527	.3292	.3086
FC Ethanol (reformed)	1.162	.9298	.7749	.6642	.5811	.5166	.4649	.4226	.3874	.3576	.3321	.3099	.2906
FC Petrol (Reformed)	.9076	.7261	.6051	.5186	.4538	.4034	.3630	.3300	.3025	.2793	.2593	.2420	.2269
ICE Ethanol	32.89	26.31	21.92	18.79	16.44	14.62							
ICE RME	37.84	30.27	25.23	21.62	18.92	16.82							
ICE Diesel	24.19	19.35	16.12	13.82	12.09	10.75							
ICE Methanol	18.36	14.69	12.24	10.49	9.182	8.162							
ICE Methane	15.95	12.76	10.64	9.116	7.977	7.090							
ICE Petrol	15.35	12.28	10.23	8.771	7.675	6.822							
ICE Propane	14.81	11.85	9.874	8.464	7.406	6.583							

TABLE A.16 LIFETIME NOx EMISSIONS FOR URBAN BUSES (Continued)

kg NOx/kW (Total) Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC RME (Reformed)	12.77	10.21	8.511	7.295	6.383	5.674	5.107	4.642	4.255	3.928	3.648	3.404	3.192	
FC Bioethanol (Reformed)	15.81	12.65	10.54	9.036	7.907	7.028	6.325	5.750	5.271	4.866	4.518	4.217	3.953	
FC RME (Partial Oxidation)	13.48	10.78	8.987	7.703	6.740	5.991	5.392	4.902	4.494	4.148	3.852	3.595	3.370	
FC Bioethanol (Int. Reformed)	11.84	9.472	7.893	6.766	5.920	5.262	4.736	4.305	3.947	3.643	3.383	3.157	2.960	
FC RME (Int. Reformed)	9.314	7.451	6.209	5.322	4.657	4.139	3.726	3.387	3.105	2.866	2.661	2.484	2.328	
FC Biomethanol (Reformed)	7.677	6.141	5.118	4.387	3.838	3.412	3.071	2.791	2.559	2.362	2.193	2.047	1.919	
FC Biomethanol (Int. Reformed)	5.509	4.407	3.673	3.148	2.754	2.448	2.204	2.003	1.836	1.695	1.574	1.469	1.377	
FC Diesel (Reformed)	3.658	2.926	2.439	2.090	1.829	1.626	1.463	1.330	1.219	1.126	1.045	.9755	.9145	
FC Propane (Reformed)	3.648	2.919	2.432	2.085	1.824	1.621	1.459	1.327	1.216	1.123	1.042	.9729	.9121	6.949
FC Petrol (Reformed)	3.228	2.582	2.152	1.844	1.614	1.435	1.291	1.174	1.076	.9932	.9222	.8607	.8070	6.056
FC Petrol (Partial Oxidation)	3.094	2.475	2.062	1.768	1.547	1.375	1.237	1.125	1.031	.9519	.8839	.8250	.7734	
FC Propane (Partial Oxidation)	3.113	2.490	2.075	1.779	1.556	1.383	1.245	1.132	1.038	.9577	.8893	.8300	.7782	
H2 (Electrolysis)	2.656	2.125	1.771	1.518	1.328	1.181	1.063	.9660	.8855	.8174	.7590	.7084	.6641	
FC Diesel (Partial Oxidation)	2.419	1.935	1.613	1.382	1.210	1.075	.9677	.8797	.8064	.7444	.6912	.6451	.6048	
FC Methanol (Ref.)	2.345	1.876	1.563	1.340	1.172	1.042	.9378	.8526	.7815	.7214	.6699	.6252	.5861	
FC Methane (Reformed)	2.187	1.750	1.458	1.250	1.094	.9721	.8749	.7954	.7291	.6730	.6249	.5833	.5468	
FC Propane (Int. Reformed)	2.179	1.743	1.453	1.245	1.089	.9684	.8715	.7923	.7263	.6704	.6225	.5810	.5447	
FC Petrol (Int. Reformed)	2.109	1.687	1.406	1.205	1.055	.9375	.8437	.7670	.7031	.6490	.6027	.5625	.5273	
FC Diesel (Int. Reforming)	1.629	1.303	1.086	.9310	.8147	.7241	.6517	.5925	.5431	.5013	.4655	.4345	.4073	
FC Methane (Partial Oxidation)	1.047	.8374	.6978	.5981	.5234	.4652	.4187	.3806	.3489	.3221	.2991	.2791	.2617	
FC Methane (Int. Ref.)	.7851	.6280	.5234	.4486	.3925	.3489	.3140	.2855	.2617	.2416	.2243	.2093	.1963	
FC Methanol (Int. Reformed)	.6615	.5292	.4410	.3780	.3308	.2940	.2646	.2406	.2205	.2036	.1890	.1764	.1654	
Batt. Ch. (24 hrs)									9.844	9.087	8.438	7.876	7.383	6.949
Batt. Ch. (Night)									8.58	7.92	7.354	6.864	6.435	6.056
ICE Bioethanol	46.85	37.48	31.23	26.77	23.42	20.82								
ICE RME	51.82	41.46	34.55	29.61	25.91	23.03								
ICE Diesel	26.30	21.04	17.53	15.03	13.15	11.69								
ICE Biomethanol	24.62	19.70	16.41	14.07	12.31	10.94								
ICE Methanol	19.12	15.29	12.74	10.92	9.558	8.496								
ICE Propane	17.44	13.96	11.63	9.968	8.722	7.753								
ICE Methane	16.90	13.52	11.27	9.657	8.450	7.511								
ICE Petrol	17.91	14.33	11.94	10.23	8.954	7.959								

TABLE A.17 LIFETIME NO2 EMISSIONS FOR URBAN BUSES

kg N2O/kW:														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Petrol (Reformed) (Use)	.0882	.0705	.0588	.0504	.0441	.0392	.0353	.0321	.0294	.0271	.0252	.0235	.0220	
FC Diesel (Reformed) (Use)	.0092	.0073	.0061	.0052	.0046	.0041	.0037	.0033	.0031	.0028	.0026	.0024	.0023	
Hydrogen (Electrolysis)	.0606	.0485	.0404	.0346	.0303	.0269	.0242	.0220	.0202	.0186	.0173	.0162	.0151	
Batt. Charge (24hrs)									.2244	.2072	.1924	.1796	.1683	.1584
Batt. Charge (Night)									.1422	.1313	.1219	.1138	.1067	.1004
ICE Petrol (Use)	1.069	.8552	.7127	.6108	.5345	.4751								
ICE Diesel (Use)	.1189	.0951	.0793	.0680	.0595	.0529								

TABLE A.18 LIFETIME SULPHUR DIOXIDE EMISSIONS FOR URBAN BUSES

kg SO2/kW (Fuel Production):

EFFICIENCY	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC Bioethanol (Ref.)	11.30	9.043	7.536	6.460	5.652	5.024	4.522	4.111	3.768	3.478	3.230	3.014	2.826	
FC Bioethanol (Int. Ref.)	10.28	8.221	6.851	5.872	5.138	4.567	4.111	3.737	3.426	3.162	2.936	2.740	2.569	
FC RME Partial Oxidation)	8.516	6.813	5.677	4.866	4.258	3.785	3.406	3.097	2.839	2.620	2.433	2.271	2.129	
H2 (Electrolysis)	8.131	6.505	5.421	4.646	4.066	3.614	3.253	2.957	2.710	2.502	2.323	2.168	2.033	
FC RME (Reformed)	6.472	5.178	4.315	3.698	3.236	2.876	2.589	2.353	2.157	1.991	1.849	1.726	1.618	
FC RME (Int. Reformed)	5.884	4.707	3.922	3.362	2.942	2.615	2.353	2.139	1.961	1.810	1.681	1.569	1.471	
FC Petrol (Partial Oxidation)	5.294	4.235	3.529	3.025	2.647	2.353	2.117	1.925	1.765	1.629	1.512	1.412	1.323	
FC Petrol (Reformed)	3.970	3.176	2.647	2.269	1.985	1.765	1.588	1.444	1.323	1.222	1.134	1.059	.9925	
FC Petrol (Int. Reformed)	3.609	2.887	2.406	2.062	1.805	1.604	1.444	1.312	1.203	1.111	1.031	.9625	.9023	
FC Diesel (Partial Oxidation)	3.448	2.758	2.298	1.970	1.724	1.532	1.379	1.254	1.149	1.061	.9850	.9193	.8619	
FC Propane (Partial Oxidation)	3.231	2.585	2.154	1.846	1.615	1.436	1.292	1.175	1.077	.9941	.9231	.8616	.8077	
FC Diesel (Reformed)	2.554	2.043	1.703	1.459	1.277	1.135	1.022	.9287	.8513	.7858	.7297	.6811	.6385	
FC Propane (Reformed)	2.488	1.990	1.658	1.422	1.244	1.106	.9951	.9046	.8292	.7655	.7108	.6634	.6219	
FC Diesel (Int. Reformed)	2.322	1.857	1.548	1.327	1.161	1.032	.9287	.8443	.7739	.7144	.6634	.6191	.5804	
FC Propane (Int. Reformed)	2.262	1.809	1.508	1.292	1.131	1.005	.9046	.8224	.7539	.6959	.6462	.6031	.5654	
FC Methane (Partial Oxidation)	1.886	1.509	1.258	1.078	.9432	.8384	.7546	.6860	.6288	.5804	.5390	.5030	.4716	
FC Biomethanol (Ref.)	1.568	1.254	1.045	.8959	.7839	.6968	.6271	.5701	.5226	.4824	.4480	.4181	.3920	
FC Methane (Reformed)	1.555	1.244	1.037	.8888	.7777	.6913	.6221	.5656	.5184	.4786	.4444	.4148	.3888	
FC Biomethanol (Int. Reformed)	1.425	1.140	.9502	.8145	.7127	.6335	.5701	.5183	.4751	.4386	.4072	.3801	.3563	
FC Methane (Int. Reformed)	1.414	1.131	.9426	.8080	.7070	.6284	.5656	.5142	.4713	.4351	.4040	.3770	.3535	
Battery (24 hrs ch.)									30.13	27.82	25.83	24.11	22.6	21.27
Battery (Night ch.)									23.98	22.13	20.55	19.18	17.98	16.93
ICE Ethanol	12.12	9.693	8.077	6.923	6.058	5.385								
ICE RME	8.831	7.065	5.888	5.046	4.416	3.925								
ICE Petrol	4.376	3.501	2.918	2.501	2.188	1.945								
ICE Diesel	3.010	2.408	2.007	1.720	1.505	1.338								
ICE Propane	2.733	2.187	1.822	1.562	1.367	1.215								
ICE Biomethanol	1.619	1.295	1.079	.9251	.8095	.7195								
ICE Methane	1.879	1.503	1.253	1.074	.9395	.8351								

TABLE A.19 LIFETIME PM EMISSIONS FOR URBAN BUSES

kg PM/kW (Use):													
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8
FC Diesel (Reformed)	.3096	.2477	.2064	.1769	.1548	.1376	.1239	.1126	.1032	.0953	.0885	.0826	.0774
FC RME (Reformed)	.2478	.1983	.1652	.1416	.1239	.1101	.0991	.0901	.0826	.0763	.0708	.0661	.0620
FC Methanol (Reformed)	.1352	.1081	.0901	.0772	.0676	.0601	.0541	.0492	.0451	.0416	.0386	.0360	.0338
FC Ethanol (Reformed)	.0972	.0777	.0648	.0555	.0486	.0432	.0389	.0353	.0324	.0299	.0278	.0259	.0243
FC Propane (Reformed)	.0733	.0587	.0489	.0419	.0367	.0326	.0293	.0267	.0244	.0226	.0209	.0196	.0183
FC Petrol (Reformed)	.0791	.0633	.0527	.0452	.0396	.0352	.0316	.0288	.0264	.0243	.0226	.0211	.0198
FC Methane (Reformed)	.0408	.0326	.0272	.0233	.0204	.0181	.0163	.0148	.0136	.0126	.0117	.0109	.0102
ICE Diesel	4.014	3.211	2.676	2.294	2.007	1.784							
ICE RME	3.720	2.976	2.480	2.126	1.860	1.653							
ICE Methanol	1.535	1.228	1.024	.8774	.7677	.6824							
ICE Ethanol	1.146	.9165	.7638	.6547	.5728	.5092							
ICE Petrol	.9593	.7675	.6396	.5482	.4797	.4264							
ICE Propane	.8860	.7088	.5907	.5063	.4430	.3938							
ICE Methane	.4918	.3934	.3279	.2810	.2459	.2186							

TABLE A.19 LIFETIME PM EMISSIONS FOR URBAN BUSES (Continued):

kg PM/kW (Total):														
Efficiency	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85
FC RME (Partial Oxidation)	2.000	1.600	1.333	1.143	.9998	.8888	.7999	.7272	.6666	.6153	.5713	.5333	.4999	
FC Bioethanol (Reformed)	2.179	1.743	1.453	1.245	1.089	.9684	.8716	.7924	.7263	.6705	.6226	.5811	.5447	
FC RME (Reformed)	1.768	1.414	1.178	1.010	.8838	.7856	.7070	.6427	.5892	.5439	.5050	.4713	.4419	
FC Bioethanol (Int. Reformed)	1.893	1.514	1.262	1.081	.9463	.8411	.7570	.6882	.6309	.5823	.5407	.5047	.4731	
FC RME (Int. Reformed)	1.382	1.105	.9211	.7895	.6908	.6140	.5526	.5024	.4605	.4251	.3947	.3684	.3454	
FC Biomethanol (Reformed)	.6115	.4892	.4077	.3494	.3057	.2718	.2446	.2224	.2038	.1882	.1747	.1631	.1529	
FC Biomethanol (Int. Reformed)	.4329	.3463	.2886	.2474	.2164	.1924	.1732	.1574	.1443	.1332	.1237	.1154	.1082	
FC Diesel (Reformed)	.3152	.2522	.2102	.1801	.1576	.1401	.1261	.1146	.1051	.0970	.0901	.0841	.0788	
H2 (Electrolysis)	.1949	.1559	.1299	.1114	.0974	.0866	.0780	.0709	.0650	.0600	.0557	.0520	.0487	
FC Propane (Reformed)	.1037	.0829	.0691	.0592	.0518	.0461	.0415	.0377	.0346	.0319	.0296	.0276	.0259	
FC Petrol (Reformed)	.0848	.0679	.0566	.0485	.0424	.0377	.0339	.0309	.0283	.0261	.0242	.0226	.0212	
FC Methane (Reformed)	.0408	.0326	.0272	.0233	.0204	.0181	.0163	.0148	.0136	.0126	.0117	.0109	.0102	
FC Propane (Partial Oxidation)	.0394	.0315	.0263	.0225	.0197	.0175	.0158	.0143	.0131	.0121	.0113	.0105	.0099	
FC Propane (Int. Reformed)	.0276	.0221	.0184	.0158	.0138	.0123	.0110	.0100	.0092	.0085	.0079	.0074	.0069	
FC Petrol (Partial Oxidation)	.0076	.0061	.0051	.0044	.0038	.0034	.0031	.0028	.0025	.0024	.0022	.0020	.0019	
FC Diesel (Partial Oxidation)	.0076	.0060	.0050	.0043	.0038	.0034	.0030	.0027	.0025	.0023	.0022	.0020	.0019	
FC Petrol (Int. Reforming)	.0052	.0042	.0035	.0030	.0026	.0023	.0021	.0019	.0017	.0016	.0015	.0014	.0013	
FC Diesel (Int. Reformed)	.0051	.0041	.0034	.0029	.0025	.0023	.0020	.0019	.0017	.0016	.0015	.0014	.0013	
Battery Charge (24hrs)									.7222	.6667	.6190	.5778	.5417	.5098
Battery Charge (Night)									.5222	.4821	.4476	.4178	.3917	.3686
ICE RME	5.793	4.635	3.862	3.311	2.897	2.575								
ICE Diesel	4.020	3.216	2.680	2.297	2.010	1.787								
ICE Bioethanol	3.377	2.701	2.251	1.930	1.688	1.501								
ICE Biomethanol	2.027	1.622	1.351	1.158	1.014	.9010								
ICE Propane	1.805	1.444	1.204	1.032	.9027	.8024								
ICE Petrol	.9657	.7725	.6438	.5518	.4828	.4292								
ICE Methane	.4918	.3934	.3279	.2810	.2459	.2186								

TABLE A.20 EMISSIONS FOR BATTERY RECHARGING

Fuel Cell Power Station with 0.70 Battery Efficiency:					
Fuel Cell Efficiency	.45	.5	.55	.6	.65
kgH2/kWh	.1059	.0953	.0866	.0794	.0733
Methane (Internally Reformed):					
kgCH4/kWh	.2106	.1896	.1723	.1580	.1458
kgCO2/kWh (Usage)	.5792	.5213	.4739	.4344	.4010
kgCO2/kWh (Production)	.0562	.0505	.0460	.0421	.0389
TOTAL kgCO2/kWh	.6354	.5719	.5199	.4766	.4399
gCO/kWh (Production)	.0222	.0200	.0182	.0167	.0154
gNOx/kWh (Production)	.1662	.1495	.1359	.1246	.1150
gNMVOC/kWh (Production)	.4294	.3865	.3513	.3221	.2973
gCH4/kWh (Production)	2.560	2.304	2.095	1.920	1.772
gSO2/kWh (Production)	.3300	.2970	.2700	.2475	.2284
Methane ((Reformed):					
kgCH4/kWh	.2317	.2085	.1896	.1738	.1604
kgCO2/kWh (Usage)	.6372	.5735	.5213	.4779	.4411
kgCO2/kWh (Production)	.0618	.0556	.0505	.0463	.0428
TOTAL kgCO2/kWh	.6989	.6291	.5719	.5242	.4839
gCO/kWh (Usage)	.1053	.0948	.0862	.0790	.0729
gCO/kWh (Production)	.0245	.0220	.0200	.0183	.0169
TOTAL gCO/kWh	.1298	.1168	.1062	.0973	.0898
gNOx/kWh(Usage)	.2801	.2521	.2292	.2101	.1939
gNOx/kWh (Production)	.1828	.1645	.1495	.1371	.1265
TOTAL gNOx/kWh	.4629	.4166	.3787	.3472	.3205
gNMVOC/kWh (Usage)	.0211	.0190	.0172	.0158	.0146
gNMVOC/kWh (Production)	.4724	.4251	.3865	.3543	.3270
TOTAL gNMVOC/kWh	.4934	.4441	.4037	.3701	.3416
gCH4/kWh (Usage)	.2801	.2521	.2292	.2101	.1939
gCH4/kWh (Production)	2.806	2.525	2.296	2.104	1.943
TOTAL gCH4/kWh	3.086	2.777	2.525	2.314	2.136
gSO2/kWh (Production)	.3630	.3267	.2970	.2722	.2513
gPM/kWh (Usage)	.0053	.0047	.0043	.0040	.0037
Methane (Partial Oxidation):					
kgCH4/kWh	.2808	.2528	.2298	.2106	.1944
kgCO2/kWh (Usage)	.7765	.6988	.6353	.5824	.5376
kgCO2/kWh (Production)	.0749	.0674	.0613	.0562	.0518
TOTAL kgCO2/kWh	.8514	.7662	.6966	.6385	.5894
gCO/kWh (Production)	.0296	.0267	.0243	.0222	.0205
gNOx/kWh (Production)	.2215	.1994	.1813	.1662	.1534
gNMVOC/kWh (Production)	.5726	.5153	.4685	.4294	.3964
gCH4/kWh (Production)	3.413	3.072	2.793	2.560	2.363
gSO2/kWh (Production)	.4399	.3960	.3600	.3300	.3046
Diesel (Internally Reformed):					
kgDiesel/kWh	.2427	.2184	.1986	.1820	.1680
kgCO2/kWh (Usage)	.7560	.6804	.6186	.5670	.5234
kgCO2/kWh (Production)	.0744	.0669	.0608	.0558	.0515
TOTAL kgCO2/kWh	.8304	.7473	.6794	.6228	.5749
gCO/kWh (Production)	.0453	.0407	.0370	.0339	.0313
gNOx/kWh (Production)	.3448	.3103	.2821	.2586	.2387
gNMVOC/kWh (Production)	.9871	.8884	.8076	.7403	.6834
gCH4/kWh (Production)	.1573	.1416	.1287	.1180	.1089
gSO2/kWh (Production)	.4914	.4422	.4020	.3685	.3402
gPM/kWh (Production)	.0011	.0010	.0009	.0008	.0007

TABLE A.20 EMISSIONS FOR BATTERY RECHARGING
(Continued)

Fuel Cell Power Station with 0.70 Battery Efficiency:					
Fuel Cell Efficiency	.45	.5	.55	.6	.65
Diesel (Reformed):					
kgDiesel/kWh	.2670	.2403	.2184	.2002	.1848
kgCO2/kWh (Usage)	.8334	.7501	.6819	.6250	.5770
kgCO2/kWh (Production)	.0826	.0743	.0676	.0620	.0572
TOTAL kgCO2/kWh	.9160	.8244	.7495	.6870	.6342
gCO/kWh (Usage)	.5339	.4805	.4369	.4005	.3697
gCO/kWh (Production)	.0498	.0448	.0407	.0373	.0345
TOTAL gCO/kWh	.5837	.5254	.4776	.4378	.4041
gNOx/kWh (Usage)	.3949	.3554	.3231	.2962	.2734
gNOx/kWh (Production)	.3793	.3414	.3103	.2845	.2626
TOTAL gNOx/kWh	.7742	.6968	.6334	.5806	.5360
gNMVOC/kWh (Usage)	.0993	.0893	.0812	.0744	.0687
gNMVOC/kWh (Production)	1.086	.9772	.8884	.8143	.7517
TOTAL gNMVOC/kWh	1.185	1.067	.9696	.8888	.8204
gCH4/kWh (Usage)	.0046	.0042	.0038	.0035	.0032
gCH4/kWh (Production)	.1731	.1558	.1416	.1298	.1198
TOTAL gCH4/kWh	.1777	.1599	.1454	.1333	.1230
gN2O/kWh (Usage)	.0019	.0017	.0016	.0015	.0013
gSO2/kWh (Production)	.5405	.4865	.4422	.4054	.3742
gPM/kWh (Usage)	.0170	.0153	.0139	.0127	.0118
gPM/kWh (Production)	.0012	.0011	.0010	.0009	.0008
TOTAL gPM/kWh	.0182	.0164	.0149	.0136	.0126
Diesel (Partial Oxidation):					
kgDiesel/kWh	.3604	.3243	.2949	.2703	.2495
kgCO2/kWh (Usage)	1.129	1.016	.9241	.8471	.7819
kgCO2/kWh (Production)	.1104	.0994	.0903	.0828	.0764
TOTAL kgCO2/kWh	1.240	1.116	1.014	.9299	.8583
gCO/kWh (Production)	.0672	.0605	.0550	.0504	.0465
gNOx/kWh (Production)	.5120	.4608	.4189	.3840	.3545
gNMVOC/kWh (Production)	1.466	1.319	1.199	1.099	1.015
gCH4/kWh (Production)	.2336	.2102	.1911	.1752	.1617
gSO2/kWh (Production)	.7296	.6567	.5970	.5472	.5051
gPM/kWh (Production)	.0016	.0014	.0013	.0012	.0011

TABLE A.20 EMISSIONS FOR BATTERY RECHARGING
(Continued)

Current Mix of Power Stations:					
Battery Efficiency	.6	.65	.7	.75	.8
kgCO2/kWh	.9446	.8720	.8097	.7557	.7085
gCO/kWH	.3	.2769	.2571	.24	.225
gNOx/kWh	2.574	2.376	2.206	2.059	1.931
gNMVOC/kWh	.0388	.0358	.0333	.0311	.0291
gCH4/kWh	2.999	2.769	2.571	2.399	2.250
gSO2/kWh	7.193	6.64	6.166	5.755	5.395
gPM/kWh	.1567	.1446	.1343	.1253	.1175
gN2O/kWh	.0427	.0394	.0366	.0341	.032

TABLE A.21 EMISSIONS FOR ELECTRIC VEHICLES WITH OVERHEAD CABLES

Fuel Cell Power Station with 0.85 Electric Drive Efficiency:					
Fuel Cell Efficiency	.45	.5	.55	.6	.65
kgH2/kWh	.0785	.0706	.0642	.0589	.0543
Methane (Internally Reformed):					
kgCH4/kWh (Int. Reformed)	.1561	.1405	.1277	.1171	.1081
kgCO2/kWh (Usage)	.4283	.3855	.3504	.3212	.2965
kgCO2/kWh (Production)	.0416	.0375	.0341	.0312	.0288
TOTAL kgCO2/kWh	.4699	.4229	.3845	.3524	.3253
gCO/kWh (Production)	.0165	.0148	.0135	.0124	.0114
gNOx/kWh (Production)	.1231	.1108	.1008	.0924	.0853
gNMVOC/kWh (Production)	.3183	.2864	.2604	.2387	.2203
gCH4/kWh (Production)	1.898	1.708	1.553	1.423	1.314
gSO2/kWh (Production)	.2446	.2201	.2001	.1834	.1693
Methane (Reformed):					
kgCH4/kWh (Reformed)	.1717	.1546	.1405	.1288	.1189
kgCO2/kWh (Usage)	.4712	.4241	.3856	.3534	.3262
kgCO2/kWh (Production)	.0458	.0412	.0375	.0343	.0317
TOTAL kgCO2/kWh	.5170	.4653	.4230	.3878	.3579
gCO/kWh (Usage)	.0781	.0703	.0639	.0585	.0540
gCO/kWh (Production)	.0181	.0163	.0148	.0136	.0125
TOTAL gCO/kWh	.0962	.0866	.0787	.0721	.0666
gNOx/kWh(Usage)	.2076	.1869	.1699	.1557	.1437
gNOx/kWh (Production)	.1355	.1219	.1108	.1016	.0938
TOTAL gNOx/kWh	.3431	.3088	.2807	.2573	.2375
gNMVOC/kWh (Usage)	.0156	.0141	.0128	.0117	.0108
gNMVOC/kWh (Production)	.3501	.3151	.2864	.2626	.2424
TOTAL gNMVOC/kWh	.3657	.3291	.2992	.2743	.2532
gCH4/kWh (Usage)	.2076	.1869	.1699	.1557	.1437
gCH4/kWh (Production)	2.080	1.872	1.702	1.560	1.440
TOTAL gCH4/kWh	2.287	2.059	1.871	1.715	1.583
gSO2/kWh (Production)	.2690	.2421	.2201	.2018	.1862
gPM/kWh (Usage)	.0039	.0035	.0032	.0029	.0027
Methane (Partial Oxidation):					
kgCH4/kWh (Partial Oxidation)	.2082	.1873	.1703	.1561	.1441
kgCO2/kWh (Usage)	.5711	.5140	.4672	.4283	.3954
kgCO2/kWh (Production)	.0555	.0500	.0454	.0416	.0384
TOTAL CO2/kWh	.6266	.5639	.5126	.4699	.4338
gCO/kWh (Production)	.0220	.0198	.0180	.0165	.0152
gNOx/kWh (Production)	.1642	.1478	.1343	.1231	.1137
gNMVOC/kWh (Production)	.4244	.3819	.3472	.3183	.2938
gCH4/kWh (Production)	2.530	2.277	2.070	1.898	1.752
gSO2/kWh (Production)	.3261	.2935	.2668	.2446	.2257
Diesel (Internally Reformed):					
kgDiesel/kWh (Int. Reformed)	.1799	.1619	.1472	.1349	.1245
kgCO2/kWh (Usage)	.5594	.5035	.4577	.4196	.3873
kgCO2/kWh (Production)	.0551	.0496	.0451	.0413	.0382
TOTAL kgCO2/kWh	.6145	.5531	.5028	.4609	.4254
gCO/kWh (Production)	.0335	.0302	.0274	.0252	.0232
gNOx/kWh (Production)	.2556	.2300	.2091	.1917	.1769
gNMVOC/kWh (Production)	.7316	.6584	.5986	.5487	.5065
gCH4/kWh (Production)	.1166	.1049	.0954	.0875	.0807
gSO2/kWh (Production)	.3642	.3278	.2980	.2732	.2521
gPM/kWh (Production)	.0008	.0007	.0007	.0006	.0006

TABLE A.21 EMISSIONS FOR ELECTRIC VEHICLES WITH OVERHEAD CABLES (Continued)

Fuel Cell Power Station with 0.85 Electric Drive Efficiency:					
Fuel Cell Efficiency	.45	.5	.55	.6	.65
Diesel (Reformed):					
kgDiesel/kWh (Reformed)	.1979	.1781	.1619	.1484	.1370
kgCO2/kWh (Usage)	.6168	.5551	.5046	.4626	.4270
kgCO2/kWh (Production)	.0606	.0546	.0496	.0455	.0420
TOTAL kgCO2/kWh	.6774	.6096	.5542	.5080	.4690
gCO/kWh (Usage)	.3957	.3562	.3238	.2968	.2740
gCO/kWh (Production)	.0369	.0332	.0302	.0277	.0255
TOTAL gCO/kWh	.4326	.3894	.3540	.3245	.2995
gNOx/kWh (Usage)	.2927	.2634	.2395	.2195	.2026
gNOx/kWh (Production)	.2811	.2530	.2300	.2109	.1946
TOTAL gNOx/kWh	.5738	.5164	.4695	.4304	.3973
gNMVOC/kWh (Usage)	.0736	.0662	.0602	.0552	.0509
gNMVOC/kWh (Production)	.8048	.7243	.6584	.6036	.5571
TOTAL gNMVOC/kWh	.8783	.7905	.7186	.6587	.6081
gCH4/kWh (Usage)	.0034	.0031	.0028	.0026	.0024
gCH4/kWh (Production)	.1283	.1154	.1049	.0962	.0888
TOTAL gCH4/kWh	.1317	.1185	.1077	.0988	.0912
gN2O/kWh (Usage)	.0014	.0013	.0012	.0011	.0010
gSO2/kWh (Production)	.4006	.3606	.3278	.3005	.2774
gPM/kWh (Usage)	.0126	.0113	.0103	.0094	.0087
gPM/kWh (Production)	.0009	.0008	.0007	.0007	.0006
TOTAL gPM/kWh	.0135	.0121	.0110	.0101	.0093
Diesel (Partial Oxidatiuon):					
kgDiesel/kWh (Partial Oxidation)	.2671	.2404	.2185	.2003	.1849
kgCO2/kWh (Usage)	.8306	.7476	.6796	.6230	.5751
kgCO2/kWh (Production)	.0818	.0736	.0670	.0614	.0567
TOTAL kgCO2/kWh	.9125	.8212	.7466	.6843	.6317
gCO/kWh (Production)	.0498	.0448	.0408	.0374	.0345
gNOx/kWh (Production)	.3795	.3415	.3105	.2846	.2627
gNMVOC/kWh (Production)	1.086	.9777	.8888	.8147	.7521
gCH4/kWh (Production)	.1731	.1558	.1417	.1299	.1199
gSO2/kWh (Production)	.5408	.4867	.4425	.4056	.3744
gPM/kWh (Production)	.0012	.0011	.0010	.0009	.0008

TABLE A.21 EMISSIONS FOR ELECTRIC VEHICLES WITH OVERHEAD CABLES (Continued)

Current Mix of Power Stations:				
Electric Drive Efficiency	.75	.8	.85	.9
kgCO2/kWh	.6801	.6376	.6001	.5668
gCO/kWH	.216	.2025	.1906	.18
gNOx/kWh	1.853	1.737	1.635	1.544
gNMVOC/kWh	.0276	.0259	.0243	.0230
gCH4/kWh	2.160	2.025	1.905	1.800
gSO2/kWh	5.179	4.856	4.570	4.316
gPM/kWh	.1152	.108	.1016	.096
gN2O/kWh	.0307	.0288	.0271	.0256